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NPS CubeSat launcher design, process and requirements

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MONTEREY, CALIFORNIA

THESIS

NPS CUBESAT LAUNCHER DESIGN, PROCESS AND REQUIREMENTS

by

Matthew Richard Crook

June 2009

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13. ABSTRACT (maximum 200 words)

Access to space has always been a challenge, especially for organizations with limited budgets. In the last decade a group of universities has overcome many of the obstacles associated with placing experiments on orbit by using a nano-satellite standard called the "CubeSat." In addition to universities many private, commercial, and government organizations are now coming to appreciate the advantages of the CubeSat standard resulting in rapid growth in the CubeSat development community. Although the CubeSat standard has helped increase access to space, the number of CubeSat launch opportunities has not increased at a rate necessary to meet demand since the hardware and processes necessary to do so do not exist. U.S. based CubeSat developers face additional challenges since almost all CubeSats are launched overseas.

This thesis proposes a solution to the lack of CubeSat launch availability called the NPS CubeSat Launcher (NPSCuL). The NPSCuL is a high capacity CubeSat launch mechanism, which could facilitate rideshare opportunities onboard U.S. launch vehicles. This thesis studies the design, program management, and advantages associated with such a device, and promote its development at the Naval Postgraduate School.

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NPS CUBESAT LAUNCHER DESIGN, PROCESS AND REQUIREMENTS

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Submitted in partial fulfillment of the
Requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Access to space has always been a challenge, especially for organizations with limited budgets. In the last decade a group of universities has overcome many of the obstacles associated with placing experiments on orbit by using a nano-satellite standard called the "CubeSat." In addition to universities many private, commercial, and government organizations are now coming to appreciate the advantages of the CubeSat standard resulting in rapid growth in the CubeSat development community. Although the CubeSat standard has helped increase access to space, the number of CubeSat launch opportunities has not increased at a rate necessary to meet demand since the hardware and processes necessary to do so does not exist. U.S. based CubeSat developers face additional challenges since almost all CubeSats are launched overseas.

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LIST OF ACRONYMS AND ABBREVIATIONS

3DP	-	3D Printing
CAD	-	Computer Aided Drafting
Cal Poly	-	California Polytechnic State University
CDS	-	CubeSat Design Specification
CG	-	Center of Gravity
COTS	-	Commercially-off-the-shelf
CSEWI	-	California Space Education and Workforce Institute
CRADA	-	Cooperative Research and Development Agreement
DARPA	-	Defense Advanced Research Projects Agency
DoD	-	Department of Defense
EELV	-	Evolved Expendable Launch Vehicle (Atlas and Delta)
ESPA	-	EELV Secondary Payload Adapter
FDM	-	Fused Deposition Modeling
GEO	-	Geosynchronous Orbit
ITAR	-	International Traffic in Arms Regulations
LEO	-	Low Earth Orbit
NASA	-	National Aeronautics and Space Administration
NASA Ames	-	(NASA) Ames Research Center
NCQ	-	NPS CubeSat Queue
NPS	-	Naval Postgraduate School
NPSAT1	-	NPS Satellite 1
NPSCuL	-	NPS CubeSat Launcher
PANSAT	-	Petite Amateur Naval Satellite
P-POD		Poly Pico-satellite Orbital Deployer
PPG	-	Payload Planner’s Guide
PPL	-	Primary Payload
PRD	-	Process and Requirements Document
RP	-	Rapid Prototyping
SERB	-	(DoD) Space Experiments Review Board
SPL	-	Secondary Payload

SSAG	-	(NPS) Space System Academic Group
SSIP	-	(ESPA) Secondary Standard Interface Plane
STL	-	Stereo Lithography
STP	-	Space Test Program
WIRED	-	Workforce Innovation in Regional Economic Development

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Dr. Panholzer's enthusiastic support of the project was obvious. He frequently stopped by the lab where I worked to monitor the progress of my thesis.

Dan Sakoda spent hours helping me with all aspects of the project, especially those concerning the 3D printer. He was always available and willing to do whatever was needed.

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I would like to thank Felix Rossberg from the German Air Force who spent time as an exchange student at NPS. Felix conducted structural and finite element analysis of several NPSCuL design possibilities as a part of a master's thesis.

I owe a special thanks to the several students who conducted independent study on NPSCuL or have taken it on as a thesis project: Christina Hicks, Adam (Tito) Dejesus, Anthony (Tony) Harris and Matthew Erdner.

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I. CUBESAT INTRODUCTION AND HISTORY

A. WHAT ARE CUBESATS?

CubeSats are a class of very small satellites called "Nano-satellites." CubeSats refer specifically to those nano-satellites that adhere to the CubeSat Design Specification (CDS) published by the California Polytechnic State University (Cal Poly) generally with the standard unit of size of 10x10x10 cm^3 (one liter) and a weight of 1 kg [1]. The size mentioned above is the standard building block of all CubeSats and is referred to as "1 Unit" or "1U" for short. The actual size of a CubeSat may be slightly larger than 10x10x10 cm^3; specific CubeSat standards can be found in the CDS. Figure 1. below is of a standard 1U CubeSat.

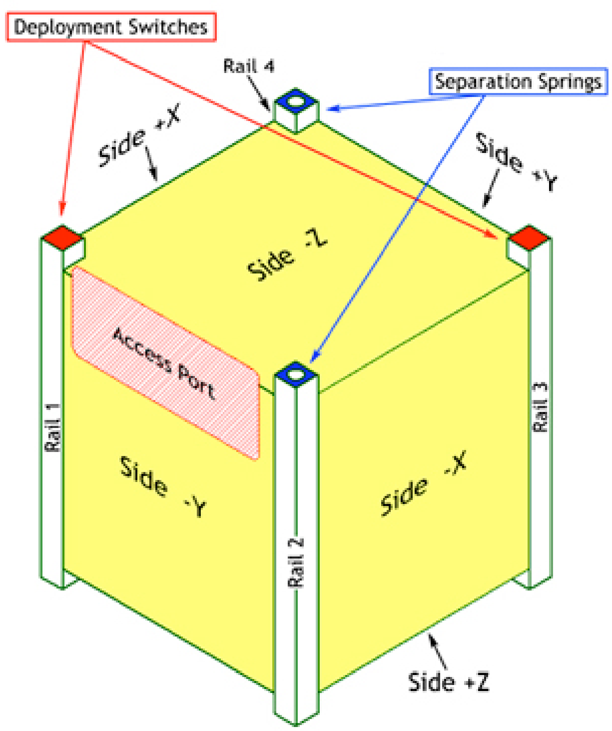

Figure 1. Standard 1U CubeSat from [1]

CubeSats are scalable and can be two to three times the length of a standard CubeSat. Existing variations include 2U (1 x 1 x 2) and 3U (1 x 1 x 3) [2]. One 2U CubeSat is the same size, weight, and approximate center of gravity (CG) as two 1U CubeSats; and one 3U is the same mass characteristics as three 1U CubeSats. Figure 2. below shows the current CubeSat family including 1U, 2U and 3U CubeSats forms [3]. In addition to the three common sizes, some have speculated usefulness for even larger sizes, such as 5U (1 x 1 x 5), 6U (1 x 2 x 3), and for imaging, 20U (2 x 2 x 5), which would allow for optics up to 20cm in diameter. In the author's opinion, the CubeSat as defined in the CDS appears to be accepted by the members of the nano-satellite development community as the de facto standard.

B. HISTORY AND DEVELOPMENT OF CUBESATS

University access to space has been limited in part due to the low number of rideshare opportunities for secondary payloads and the high development costs associated with spacecraft, even very small spacecraft. Since the beginning of the space age until the present, almost all satellites built worldwide have been one-of-a-kind, custom designed and custom built. Some commonly used spacecraft components have become available commercially-off-the-shelf (COTS), but even these components are built in relatively few numbers. Launch costs are usually very high. The paradigm in the United States and abroad on most launch vehicles, including Evolved Expendable Launch Vehicles (EELVs), such as the Atlas V and Delta IV, can be summed up as "one satellite–one launch vehicle". CubeSats represent a shift in the standard spacecraft development Paradigm.

The author believes that due to the challenges listed above, spacecraft have not been able to take advantage of economies of scale to the same extent as other highly technical industries such as computers or aircraft. Due to high development costs and few rideshare opportunities fewer colleges and universities have participated in spacecraft development than would do so

otherwise. In discussions with members of the educational aerospace community the author has observed that many believe that there are fewer U.S. college students interested in aerospace related engineering, resulting in both fewer graduates, and graduates with less hands-on experience than there could be with more frequent rideshare opportunities and lower payload development costs.

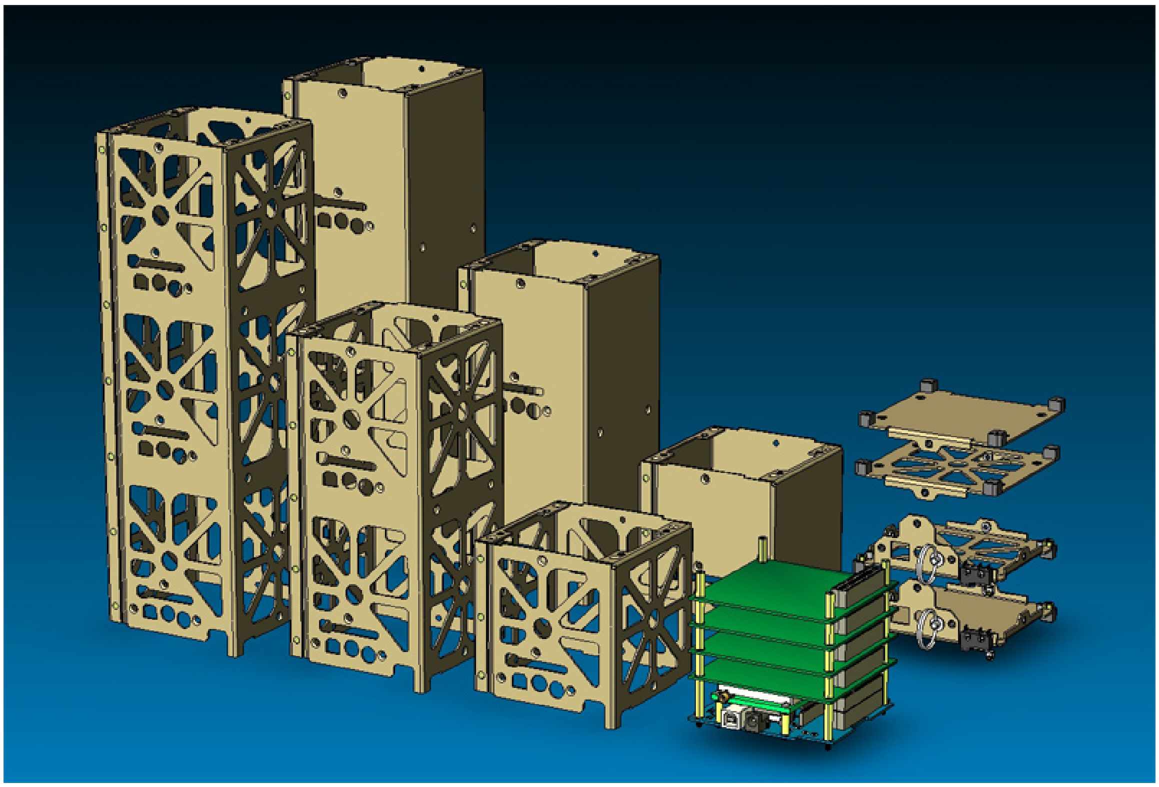

Figure 2. The CubeSat Family from [3]

Stanford and Cal Poly, in an effort to increase rideshare opportunities for small, low budget secondary payloads (SPLs), introduced the CubeSat concept. The significance of the CubeSat standard lies in the ability to standardize payloads, thereby making them interchangeable [2]. This is a dramatic shift in ideology from the current one-of-a-kind custom-built spacecraft culture. Since the size and weight of all CubeSats were standardized, a common deployment system could be employed to launch any payload conforming to the CubeSat 1U to 3U standard [2].

C. POLY PICOSATELLITE ORBITAL DEPLOYER (P-POD)

The Cal Poly Picosatellite Orbital Deployer (P-POD) was introduced shortly after the CubeSat concept had developed. Although named the "Pico-satellite" Orbital Deployer it is designed specifically to deploy CubeSats—not just any Pico-satellite [3]. The P-POD Mk I was designed to deploy 4 CubeSats [2], while the subsequent Mk II and Mk III P-PODs have each been designed to deploy 3 CubeSats [3]. Figure 3. shows a P-POD Mk II, with the naming convention that will be used for this thesis.

As mentioned earlier, CubeSats are scalable. This is an important feature because it allows the P-POD to deploy various CubeSat sizes since larger (2U and 3U) CubeSats are multiples of the basic 1U CubeSat. A P-POD Mk III can deploy a volume of 3U CubeSats, which means it could deploy one 3U CubeSat, three 1U CubeSats, or one 2U CubeSat and one 1U CubeSat without any modification to the P-POD. As mentioned earlier, since CubeSats all have approximately the same mass properties, a P-POD with any combination of CubeSats should still have approximately the same overall mass and CG characteristics as it would with any other combination, this is an important note since it makes mission planning much easier than with custom designed and built payloads where each is unique. The P-POD has been used to deploy 75% of all CubeSats launched. (See Appendix A)

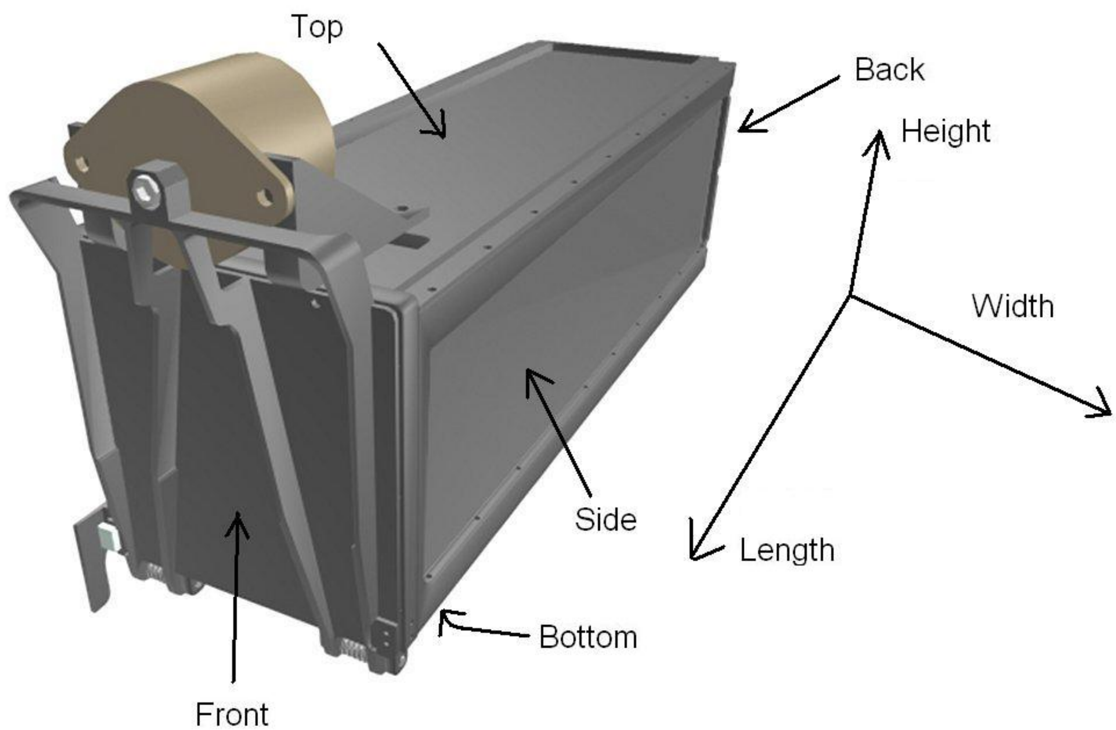

Figure 3. P-POD Mk II from [3] with Naming Convention for this Thesis.

For simplicity, the author will refer to P-PODs according to their CubeSat payload capacity. Using this convention, a P-POD with 3U worth of CubeSat payload capacity would be called a “3U P-POD”; while a P-POD with 6U worth of CubeSat payload capacity would be called a “6U P-POD” and so forth.

In addition to the 3U P-POD, there has also been a 6U P-POD in development but not yet flown. The 6U P-POD would be the same length and height as the current 3U but about twice as wide. [4]. Although the specifics of the 6U P-POD are not yet available, in the author’s opinion, developers should consider a design such that one loaded 6U P-POD should have the same mass and CG characteristics as two loaded 3U P-PODs located side by side, allowing interchangeability between a 6U P-POD and any two side by side 3U P-PODs. Additionally the width of a 6U P-POD should be such that the distance between

the rails used for attaching a 6U P-POD are the same as the outside rails of any two side-by-side 3U P-PODs including the normal gap found between two 3U P-PODs.

A 5U P-POD design (1x1x5) has been proposed that would be an extended version of the current 3U P-POD. The 5U P-POD would help use the entire volume capacity available on the Naval Postgraduate School (NPS) CubeSat Launcher (NPSCuL). Using only 3U P-PODs only 60% of the potential capacity on NPSCuL would be usable for launch. Specifics about how the 5U P-POD would help take advantage of the entire NPSCuL payload volume can be found in section 0.

D. SUMMARY OF CUBESAT LAUNCHES TO DATE

The first P-POD deployed CubeSats were launched in 2003 on the Eurokot launch vehicle, which carried six CubeSats using two of the P-POD Mk I designs. The Mk II P-POD has been used on two Russian Dnepr launch vehicles–a modified Soviet era ICBM. The first Dnepr launch in July 2006 consisted of fourteen CubeSats in five P-PODs, while the second in April 2007 consisted of seven CubeSats in three P-PODs. Unfortunately the first Dnepr launch failed to reach orbit due to a launch vehicle failure [6].

There have only been two U.S.-based CubeSat launches, both for NASA CubeSats. A U.S. Minotaur successfully launched the NASA 3U “GeneSat I” in December 2006 [4]. The second U.S.-based CubeSat launch took place on August 3, 2008 on a SpaceX Falcon 1 launch vehicle. This launch carried two NASA CubeSats the “PRESat” and “NanoSail-D”; both CubeSats were lost due to launch vehicle failure [7]. In addition to the six CubeSats launched by Germany (Eurokot – in Russia), the 21 launched by Russia, and three launched from the U.S., there was one CubeSat launched in Japan (by an M-V-8 launch vehicle, on February 22, 2006) and six launched in India by a PLSV launch vehicle on April 28, 2008. Although P-PODs are built at Cal Poly, and over half of all CubeSats have been developed in the U.S., less than 10% of CubeSats

have been launched by U.S. launch providers (See Appendix B). With the exception of NASA launching CubeSats on its own launches, no process or hardware currently exists to accommodate U.S. P-PODs on U.S. launch vehicles in general, and no CubeSat has ever been launched on an EELV (Delta IV and Atlas V launch vehicles), which tend to have the most excess launch capacity of any U.S. launch vehicle due to their large size.

E. CHALLENGES WITH FOREIGN BASED CUBESAT LAUNCHES

In the past seven years, from 2001-2008, the CubeSat community has almost doubled in size every 18 months. As more CubeSats are developed and built more CubeSat launch capacity is needed to accommodate the growing community. Given that a proven CubeSat deployment method already exists, the P-POD, which can be made compatible with a great variety of launch vehicles, including U.S. launch vehicles, one might believe that the number of CubeSat launches would increase proportionally to the amount of worldwide CubeSat development. However, by examining Figure 4. below, it is apparent that CubeSat launch volume worldwide has not dramatically increased since the first launch in 2003. This is notable especially when considering that in 2003 there were only ten CubeSat known developers worldwide compared with over 110 by 2008 [8].

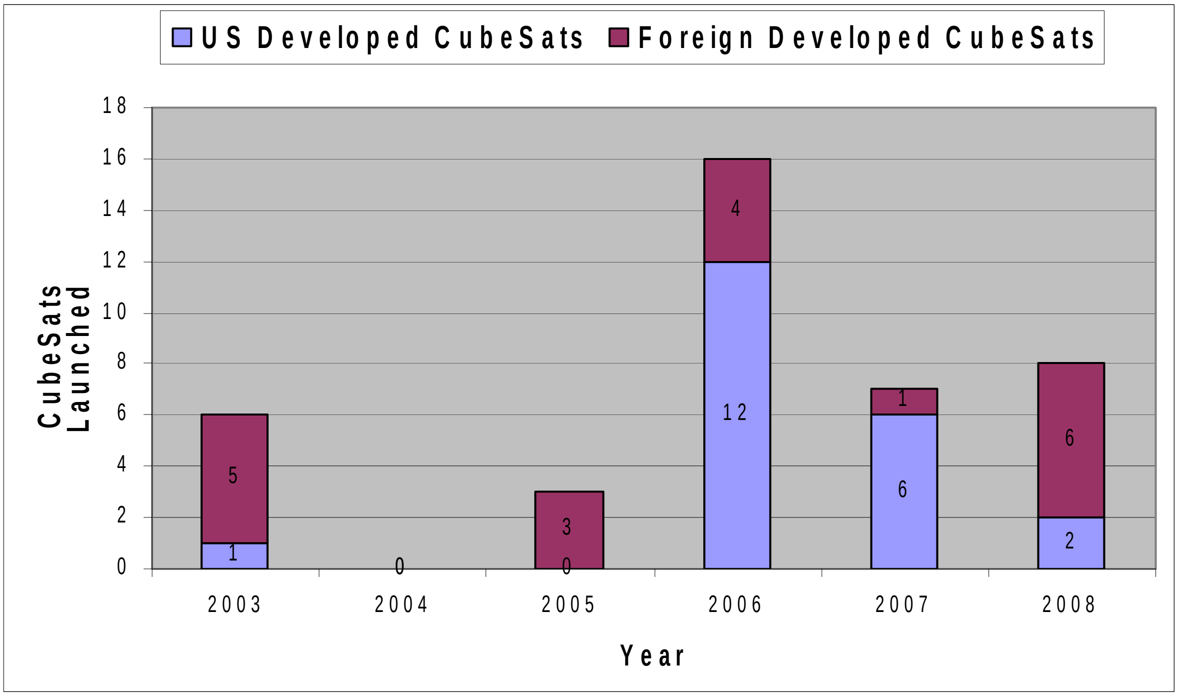

Figure 4. CubeSat Launch Volume by Year 2003–August 2008

With the exception of three CubeSats launched by NASA of which only one reached orbit, all other CubeSats launched, 37 of which 23 successfully reached orbit, have taken place outside the United States. This introduces challenges for U.S.-based CubeSat developers, who comprise over half of all CubeSat developers worldwide. U.S. CubeSat developers are regulated by the International Traffic in Arms Regulations (ITAR). ITAR restricts the export of defense-related products and technology on the United States Munitions List. Although one might not think that CubeSat technology would fall under ITAR, in fact a large amount of Aerospace technology, including some that could be used on CubeSats is regulated by ITAR. This can, in some cases, severely restrict the available technology that may be developed by U.S. innovators and colleges.

The P-POD, although it has no known defense related uses, is restricted by ITAR. Ironically, this likely forced foreign-based CubeSat developers to design their own version of the P-POD promoting foreign CubeSat innovation. The most recent foreign launch in India used the Canadian Nano-satellite Launch

System instead of the U.S. based P-POD. ITAR, while protecting U.S. technology from foreign governments, may also promote development of superior technology overseas—especially if that technology is easily replicated.

Some foreign launch providers such as ISC Kosmotras (Dnepr launch provider) have been willing to launch Cal Poly P-PODs in the past for a fee around $90,000 per 3U P-POD. The total cost to produce a flight-ready P-POD including CubeSat integration by Cal Poly is about $30,000, so the cost to launch 3U capacity on a Dnepr has been $120,000, or $40,000 per 1U Cube [4]. Although, the launch cost of $40,000 per Cube is not nearly as prohibitive as that for larger satellites, there are only a few compatible launches each year for which CubeSat can compete. Even if accepted for flight, only a few CubeSats can be launched using the P-POD alone. Cost is therefore not as prohibitive as the overall lack of launch opportunities—regardless of price.

Despite the number of willing customers CubeSats have not been included on any more than two launches world-wide in any given year. Most non-U.S. launch providers use smaller launch vehicles than those used in the U.S., so they typically have less excess mass launch capacity available for SPLs. Secondly, $90,000 is a small fee in the worldwide launch community, not enough to highly motivate launch providers to include P-PODs regularly. Many launches simply do not launch into the necessary orbit for CubeSat deployment, precluding CubeSat deployments even if the launch provider were willing and had enough excess capacity available to launch CubeSats. When a compatible launch is found, only a few P-PODs can typically be manifested, the most ever manifested was five, but there are typically fewer.

In 2008, Cal Poly reported that there are at least 113 known CubeSat developers working on over a hundred CubeSats [8]. There are likely others who do not advertise their activities because of limited man-power and/or budget constraints, which may preclude them from advertising their efforts online or at conferences. Some, such as governments or companies, may not advertise their activities for security or proprietary reasons.

Considering the relatively few launch opportunities each year for secondary payloads it seems that a reasonable solution to provide more launch opportunities for CubeSats should include a means to deploy a high number of CubeSats on a single launch. U.S. launch vehicles typically have more excess payload capacity, due to their large size, than foreign-based launch vehicles, yet there is almost no technical capacity or formal process to manifest CubeSats on U.S. launch vehicles.

F. EELV SECONDARY PAYLOAD ADAPTER (ESPA)

At the same time Cal Poly and Stanford were developing the CubeSat and P-POD, the U.S. Air Force, recognizing the weakness of the “one payload – one launch vehicle” paradigm, began development of an adapter called the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA, or “ESPA Ring”) for use on Atlas V or Delta IV launch vehicles. The ESPA is designed to replace the C-ring adapter on candidate missions where enough excess payload mass margin is available. The ESPA has six slots located around the ring, each separated by 60 degrees. The ESPA SPL envelope is 24” x 28” x 38” for the Delta IV, and 24” x 24” x 38” for the Atlas V including the interface adapter [9]. Figure 5. is a picture of an actual ESPA ring, while Figure 6. shows how an ESPA could be integrated onto an EELV payload stack.

Figure 5. ESPA Ring from [9]

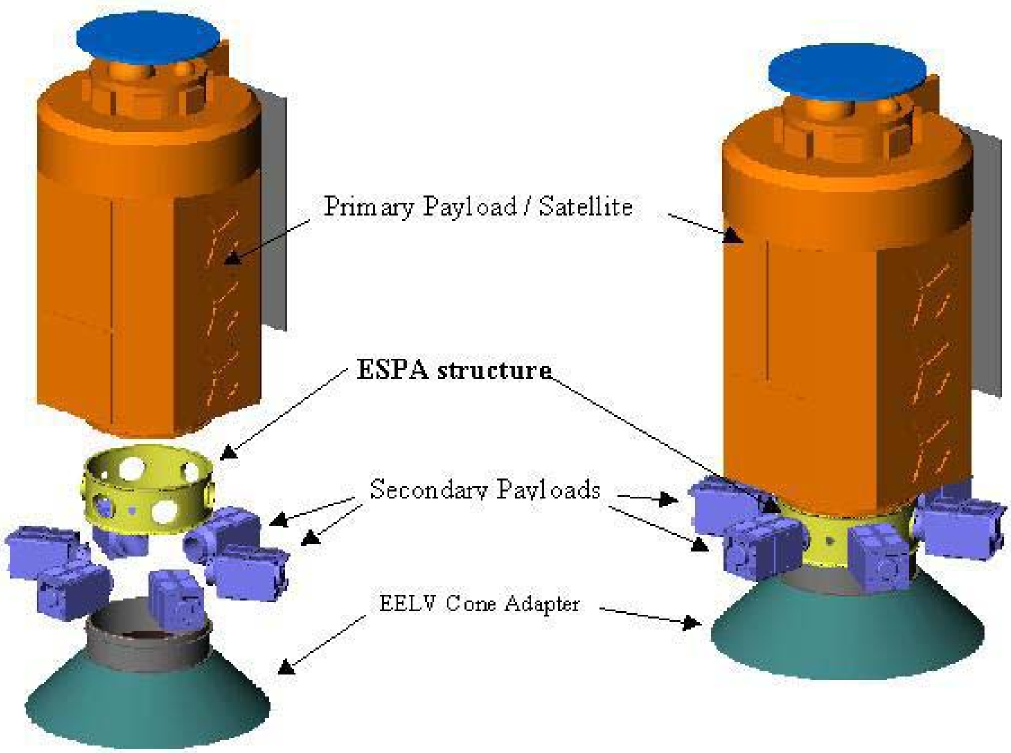

Figure 6. ESPA Integration Diagram from [9]

The first ESPA launch took place in March 2007, on the U.S. Air Force (USAF) Space Test Program (STP) mission “STP-1”. The ESPA will facilitate the use of thousands of pounds of excess payload capacity that, until recently, would have otherwise been wasted. Since large launch vehicles typically have more excess capacity than small launch vehicles, and U.S. EELVs are large launch vehicles, they are a perfect candidate for a high capacity CubeSat launch adapter.

G. NPS, THE GOVERNMENT, AND THE EDUCATIONAL REALM

NPS is in a unique position to further the launch of CubeSats onboard U.S. government and military launches. As a military institution, NPS has a working relationship with government and military entities such as the Defense Advanced Research Projects Agency (DARPA), the National Reconnaissance

Office (NRO), National Aeronautics and Space Administration (NASA), the Air Force Science and Technology Office and the DoD Space Test Program (DoD STP) among others.

As an educational institution, NPS enjoys a cordial relationship with U.S. colleges and universities, especially those closely involved with the CubeSat program, such as the Cal Poly, and Stanford University. Through programs such as the NPS CubeSat launcher, NPS is becoming a leader in the CubeSat community. Both the U.S. government and the CubeSat community have much to gain from one another. Few organizations are in a position such as NPS to foster close relationships between the educational, civil, and DoD space communities.

The government has much to gain from the CubeSat community. CubeSat technology is substantially cheaper than any other types of space born technology. Using CubeSat technology, the U.S. government could conduct experiments in space at a fraction of the cost of conventional technology. Government funding of various CubeSat programs at colleges and universities, can leverage significant expertise and manpower at a fraction of the cost of buying the same services from the private sector. There are over 50 U.S. colleges and universities actively developing CubeSats today, and this number grows substantially each year. Increased U.S. college student involvement in space-related studies such as Aerospace Engineering and Astronautical Engineering, can only serve to further the quality and quantity of U.S. space-related engineering graduates. This is an obvious advantage to both the government and U.S. space community as a whole.

U.S. Colleges and Universities have much to benefit from U.S. government involvement and funding in the CubeSat community. The government and DoD use large launch vehicles, which often have excess capacity that could be used for launching CubeSats. The CubeSat community has grown at a rapid pace, making the few launches available overseas each year inadequate to keep up with the growing demand for CubeSat launches.

With the exception of NASA, which has launched its own CubeSats, there have been no domestic CubeSat launches, and there currently exists no process or hardware necessary to manifest and launch CubeSats on U.S. launch vehicles.

H. OBJECTIVE OF THIS THESIS

The purpose of this thesis is to explore the possibility of an NPS-developed high-capacity CubeSat launcher. The CubeSat launcher will be compatible with U.S. Launch vehicles and use the flight-proven Cal Poly P-PODs. This thesis also aims to propose a process necessary to manifest U.S. CubeSats on U.S. launch vehicles on a space-available basis.

This thesis also fulfills the requirements of the grant from the Department of Labor's Workforce Innovation in Regional Economic Development (WIRED) initiative, administered by the California Space Education and Workforce Institute (CSEWI) for $20,000 [11]. As part of the agreement between NPS and CSEWI, NPS was tasked to deliver the following:

1) A functional prototype for the purpose of concept demonstration.
2) An NPSCuL process and requirements document describing the steps and requirements necessary to certify and manifest a CubeSat for launch on NPSCuL.

In addition to the deliverables required for the NPS/CSEWI agreement, the thesis conducts the following activities:

1) Concept study of NPSCuL mass re-configuration.
2) Analysis of the NPSCuL Process & Requirements document required by CSEWI.
3) Documents NPSCuL presentations at various proceedings conferences including:
    a) The DoD Rideshare Conference at Wallops Flight Facility, VA, July 2008.

b) The 2008 Summer CubeSat Workshop, preceding the Small Satellite conference in Logan, Utah, August 2008.

c) The Navy Space Experiments Review Board in Washington D.C. (at NRL) in July 2008.

d) The Department of Defense (DoD) Space Experiments Review Board in Washington D.C. (at NRL) in October 2008.

4) Seeks funding for a qualification and flight NPSCuL from interested government organizations.

II. NPS CUBESAT LAUNCHER CONCEPT

A. GENESIS OF NPSCUL

1. NPS and Small Satellites

a. PANSAT

The Naval Postgraduate School (NPS) Space Systems Academic Group (SSAG) has been involved with the design and construction of small satellites for more than two decades. The first NPS satellite successfully flown, the Petite Amateur Naval Satellite (PANSAT) was begun in 1990 and was, launched onboard the Space Shuttle in 1998. In addition to training military officers in the design and operation of satellites, PANSAT operated in the amateur radio frequency range (HAM radio frequencies). Although PANSAT had a two year design life, it operated for almost four years [12].

Figure 7. PANSAT Deploys on STS-95 from [12]

b. NPSAT1

NPSAT1 is the next small satellite to be built at NPS after PANSAT. The SSAG began development of NPSAT1 shortly after the launch of PANSAT and expects to demonstrate several COTS technologies. Unlike PANSAT, NPSAT1 is not designed to be deployed from the space shuttle but rather from an ESPA slot on a U.S. EELV [13]. NPSAT1 was manifested onboard STP-1, launched March 7, 2007, but was unable to make the flight for various reasons.

When NPSAT1 missed its manifested flight, NPS provided a mass simulator to maintain the proper CG and mass properties originally anticipated for the launch vehicle. Although the mass simulator provided the proper mass and CG characteristics expected for NPSAT1, it was non-functional.

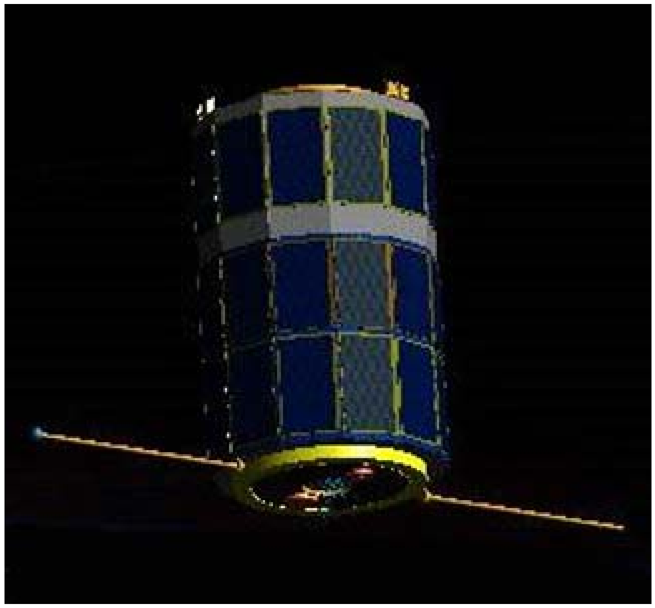

Figure 8. - NPSAT1 from [13]

2. The NPSCuL Concept is Born

Replacing NPSAT1 with a non-functional mass simulator was a disappointment. Yet, of the six ESPA payload slots, one slot was manifested empty as there were no other payloads ready to be launched. Nonetheless, it became apparent that small satellites might miss their flight when manifested on the ESPA ring as there would be six possibilities to miss any given flight. Traditionally, in the "one payload—one launch vehicle" world, if a payload was not ready in time for a flight, the launch vehicle would be delayed and wait for the finished payload. Secondary payloads on the other hand are not integral to the primary mission, so they would be left behind if necessary.

Since ESPA payloads cannot be easily substituted with any other payload, because the mass and CG properties must match the original payload, some members of the SSAG began conceptualizing a possible functional mass simulator [14]. Such a mass simulator could be mass and CG reconfigured on fairly short notice to match most SPL mass and CG characteristics and, most importantly, actually perform a useful function once in orbit.

With a simple and versatile design a launcher could carry multiple Cal Poly P-PODs on various P-POD slots and be used either as a functional mass simulator or a manifested SPL. Such a launcher could be used to take advantage of the full ESPA volume and mass capacity and launch a large volume of CubeSats when manifested. As a mass simulator, it could be mass and CG configurable by adding or subtracting ballast and P-PODs to obtain the necessary mass and CG. This concept became known as the NPS CubeSat Launcher (NPSCuL).

B. FUNCTIONAL DESCRIPTION OF NPSCUL

Although NPSCuL is called a CubeSat “launcher”, it is really a P-POD to ESPA adapter. It provides a means to attach up to ten Cal Poly P-PODs on a standard ESPA secondary payload slot, and contain all P-PODs within the ESPA secondary payload volume and mass envelope. The NPSCuL will allow P-PODs, and therefore CubeSats, to launch onboard any ESPA-compatible U.S. launcher, including the Delta IV, Atlas V and the Minotaur. In addition to simply providing substantial U.S. domestic CubeSat launch capability, NPSCuL may actually give some U.S. launch vehicles a significant advantage over foreign launch vehicles in the area of CubeSat launch volume capability.

C. DESIGN CHARACTERISTICS OF NPSCUL

1. Design Philosophy for a CubeSat Launcher

The following guidelines were set for the NPSCuL design.

1) NPSCuL must meet all necessary requirements of the ESPA Payload Planners Guide (PPG).

2) NPSCuL will carry Cal-Poly P-PODs and will not require any change in the current, proven P-POD design

3) NPSCuL should accommodate a variety of current and future P-POD designs and sizes.

4) NPSCuL must be versatile enough to meet additional requirements imposed by the primary payload.

5) NPSCuL must be mass and CG configurable.

6) The NPSCuL design should maximize the allocated volume and mass available to launch the largest volume of CubeSats possible.

7) NPSCuL may not impose requirements on the Launch Vehicle or Primary Payload (PPL) or other secondary payloads (SPL).

Mitigation of risk to the primary payload, and other secondary payloads, was the paramount design consideration above all others because of the low tolerance for risk on U.S. launches. To this end, the following additional guidelines were followed in all stages of the NPSCuL development to reduce risk to the Primary Payload and other SPLs:

1) Whenever possible NPSCuL would employ flight proven COTS technology.

2) When COTS technology is not available, other flight-proven technologies such as the P-POD would be employed.

3) When no COTS or other flight-proven technology is available, simplicity of design will take precedence over performance, mass optimization, and cost to keep risk at an absolute minimum.

4) When it will not appreciably increase risk or complexity, the NPSCuL design should be versatile enough to meet requirements imposed by any U.S. launch provider.

It was felt that practicing simplicity in the design of NPSCuL would not only minimize risk to the other payloads, but would help make the design adaptable enough for all EELV launch environments and keep the overall design and production costs low. As will be discussed later, the only major sacrifice from a simple design may be some mass margin since a simple structural design is heavier than a mass-optimized design. It was found that a simple NPSCuL structure could be fully loaded with P-PODs without exceeding the ESPA mass limit [15]. When following the ESPA SPL requirements, NPSCuL used the available volume before exceeding the available mass. Therefore, designing a simple, yet bulky design does not sacrifice payload capacity.

2. The ESPA Launch Environment

The primary launch environment considered for NPSCuL was that produced by a U.S. EELV secondary payload within an ESPA ring. The ESPA secondary standard interface plane (SSIP) is outlined in the ESPA Payload Planners' Guide. It is described below and is illustrated in Figure 9. Unless otherwise noted, anytime a coordinate system is used in this document it will always be with reference to the SSIP.

The SSIP coordinate system origin is located at the outer edge of the attachment ring at the center of the 15" adapter. The positive x direction is in the radial direction from the cylindrical center of the launch vehicle, the positive y direction is the same as the launch vehicle direction of thrust. The positive z direction is perpendicular to x-y plane such that it completes the right handed coordinate system, and tangent to the circumference of the ESPA ring.

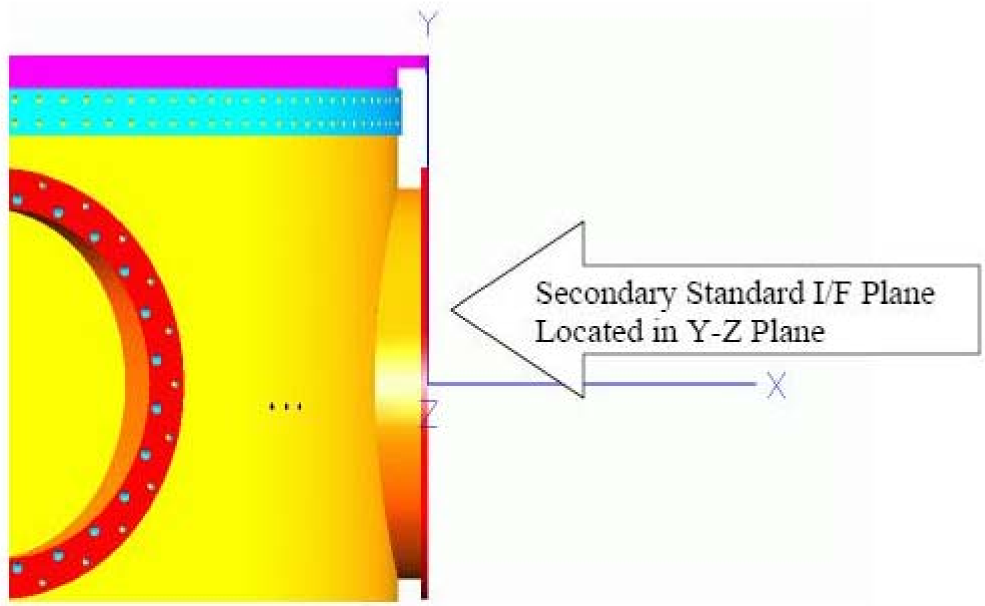

Figure 9. ESPA Secondary Standard Interface Plane (SSIP) from [9]

While the ESPA is designed to accommodate SPLs up to 400 lbs., the actual mass allowed may be less, depending on the actual excess launch capacity available. The center of gravity for any ESPA SPL should be within 20" of the SSIP, but may be up to 30" with less mass. Figure 10 below shows the allowable range for SPL CG offset from the SSIP as a function of SPL mass [9].

The ESPA SPL standard payload volume, including any attachment adapter or separation system, is 38" x 24" x 24". The Atlas V has a usable volume of 38" x 30" x 24" and the Delta IV has a usable volume of 38" x 28" x 24", however any payload designed to exceed the standard payload volume, even if still within the usable volume may be obligated to meet additional requirements. The minimum payload offset from the ESPA interface to allow enough room to mount an SPL is 2.1" in the x direction—so the usable payload volume in the x direction is 35.5". [9].

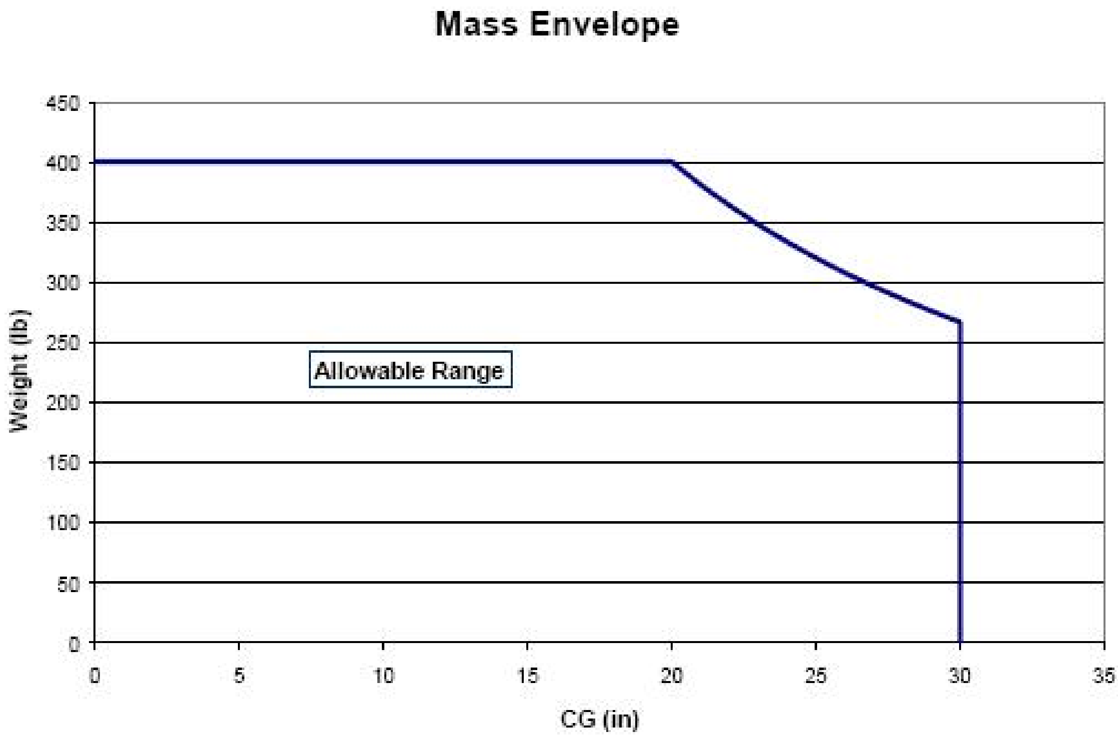

Figure 10. ESPA Mass/CG Envelope from [9]

3. NPSCuL Design Considerations

There were several design possibilities, each of which could accomplish the needed task. Conceptual NPSCuL designs began in July 2007, while finite element analysis of various concepts began in November 2007. Much of the structural analysis of the various designs considered was performed by a graduate-level German exchange student, Felix Rossberg in his thesis titled “Structural Design of a NPS CubeSat Launcher” [15]. In addition to structural analysis, there were several other considerations for the NPSCuL design. This section discusses many of the considerations for the NPSCuL design, and concludes with the selection of a design that was felt best suits the guidelines described in section 0.0.0. “Design philosophy of a CubeSat Launcher”.

a. NPSCuL Design Options

In addition to the information in the ESPA Payload Planners’ Guide there were several practical considerations for the NPSCuL design:

1 Deployment Direction. The CubeSats must deploy in such a way that there is no chance of collision with the PPL, the other SPLs, or the launch vehicle. When examining the ESPA it becomes evident that payloads could only deploy in the +x direction without restriction or in the +/- z direction if the SPLs immediately adjacent to NPSCuL had already deployed. CubeSat deployment in the +/- z direction would require the launch vehicle to deploy SPLs adjacent to NPSCuL prior to CubeSat deployment, which conflicts with guideline seven in section II.C.1 that states that NPSCuL should not impose any requirements on the launch vehicle or other payloads. This made the overall orientation of the P-PODs straight forward; the CubeSats must deploy in the +x direction. The standard ESPA volume perpendicular to the x direction is 24” x 24”, and this is the area in which the P-POD opening mechanism can be arranged to deploy CubeSats.

A P-POD deployment cross-sectional area is 5.528” by 7.575” (see Figure 11) [3]. With these constraints, there were limits to the design pattern. It was concluded that the best pattern to fit within the 24” by 24” area was two rows of four P-PODs with two P-PODs in between the two rows. (see Figure 12) This pattern also had the added benefit of consolidating excess volume in the center of the NPSCuL allowing space for assembly, a sequencer and batteries if needed [15].

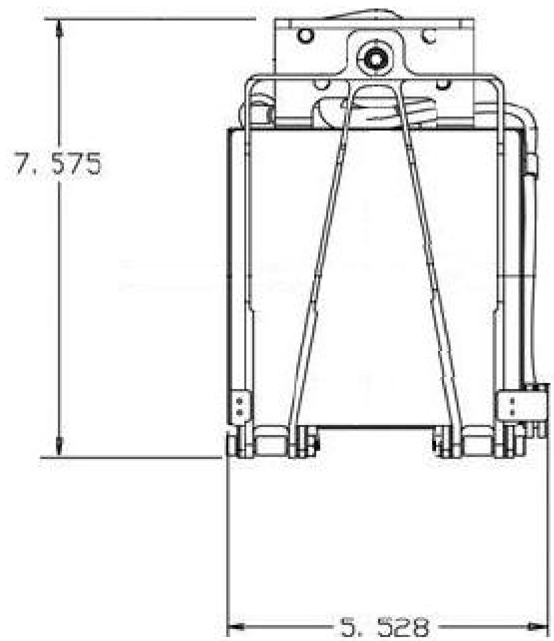

Figure 11. P-POD Mk III Cross-sectional area perpendicular to the x-direction. All Dimensions in inches.

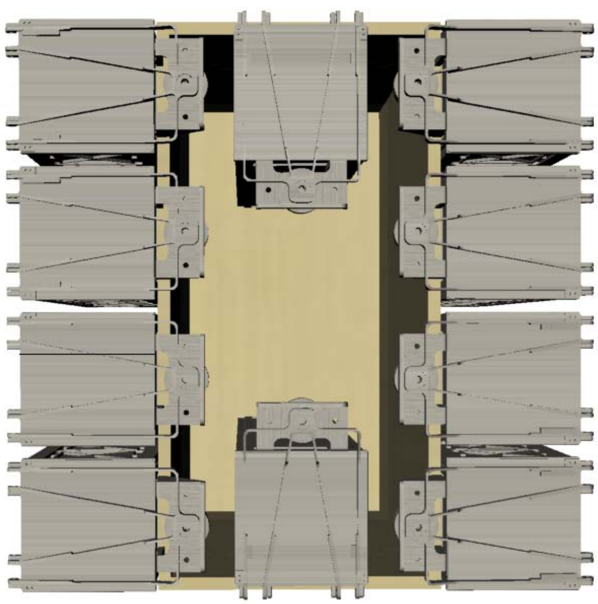

Figure 12. Preferred NPSCuL P-POD Arrangement

Various structures were considered to hold the P-PODs in the above pattern. The P-PODs could be facing inward (so the doors swing outward) or facing outward (so the doors swing inward).

2 Fully enclosed, Wrapped, or Open? There was much discussion on whether there was a need to fully enclose the P-PODs comprising the NPSCuL. The discussion centered on whether the Primary Payload (PPL) program would be safe, and just as importantly, would the PPL program manager feel safe enough with up to ten P-PODs loaded onto an ESPA slot. Would the PPL program prefer some kind of secondary enclosure around the NPSCuL or would the individual enclosures by each P-POD suffice?

It was determined that there were three options in this regard: “open”, “wrapped”, or “fully enclosed”. Each of the three options was simple, although some more than others, and could be adequate to meet the design requirements; but there were advantages that each had over the others. “Fully enclosed” meant the NPSCuL would be completely enclosed on all sides by a structure that would contain any debris, in the unlikely chance that something were to come loose from the NPSCuL or P-PODs, or in the event of an unplanned P-POD door opening. “Wrapped” was the concept of wrapping the NPSCuL in all directions except the direction in which CubeSats deploy [15]. This may provide some minor protection to the PPL and other SPLs, but not complete protection. “Open” meant there would be no requirement for an additional enclosure around any part of the NPSCuL or P-PODs. In theory, there is nothing wrong with this since P-PODs are space-qualified, have never failed, and are built to contain any launch debris produced by the CubeSats until deployment. To date, there have been no reported problems with CubeSat or P-POD debris during launch.

In the end, the “wrapped” option was discarded since it would add additional mass while adding only a marginal, if any, amount of safety. The “fully enclosed” option presented additional engineering challenges for the NPSCuL team. It would require a door covering the entire NPSCuL payload, and therefore require additional mass and mechanical complexity. In the end, it was

decided not to fully enclose the NPSCuL, and it was concluded that the simple NPSCuL design was the most robust. The P-PODs have been well tested, have been proven both on earth and on several space flights, and have performed flawlessly on each occasion. Fully enclosing an NPSCuL may produce a superficial feeling of safety, but it was felt that the increased complexity in the design and addition of moving parts will not result in a real decrease in risk to the PPL and SPLs.

3 The H and D-Structures. The H-structure, as its name suggests, is in the shape of an H but with two lines in the center. (See Figure 13) Four P-PODs would be located on the outside with the hinges on the inside. There would also be two P-PODs in the inside with the hinges toward the inside of the structure. The "D-structure" is very similar to the H-structure with the exception that the center of the "H" is pushed out towards each edge, until it resembles a D more than an H [15].

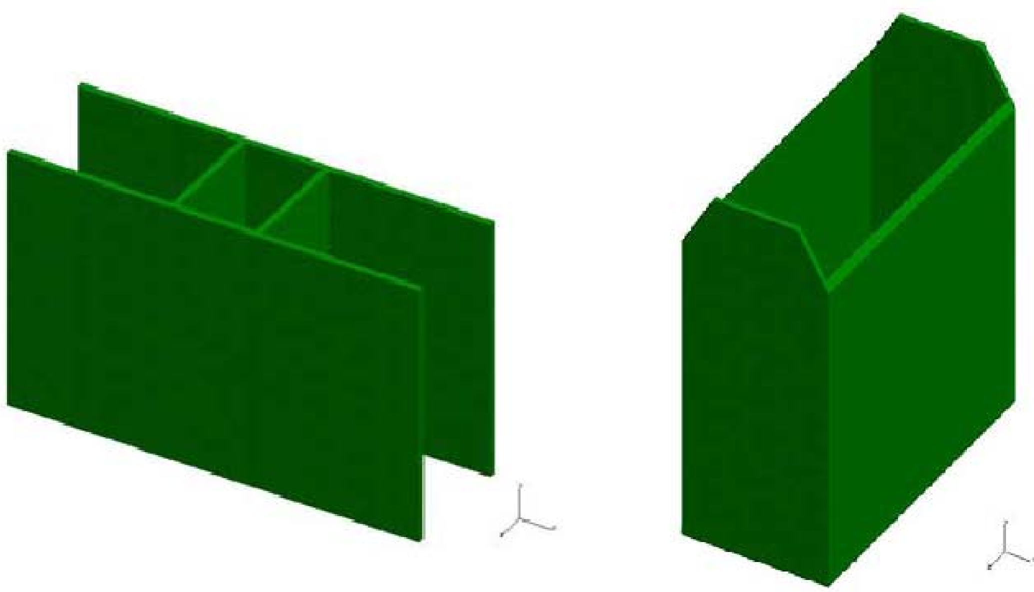

Figure 13. The Empty "H" Structure (Left) and "D" Structure (Right) from [15].

As shown in Figure 14 below, both structures were originally designed for the P-POD doors to open inward. However, in the D-structure, the two inner P-PODs were oriented 180 degrees so that the P-PODs opened to the outside. While opening to the inside with the H structure prevented any interference with equipment outside the NPSCuL payload area, it also could cause potential interference with itself. If the P-PODs were allowed to open toward the inside of NPSCuL, they could potentially block the opening or the operation of other P-PODs. Therefore, in these configurations, the sequence would be restricted so that the center P-PODs must deploy their payloads first. [15]

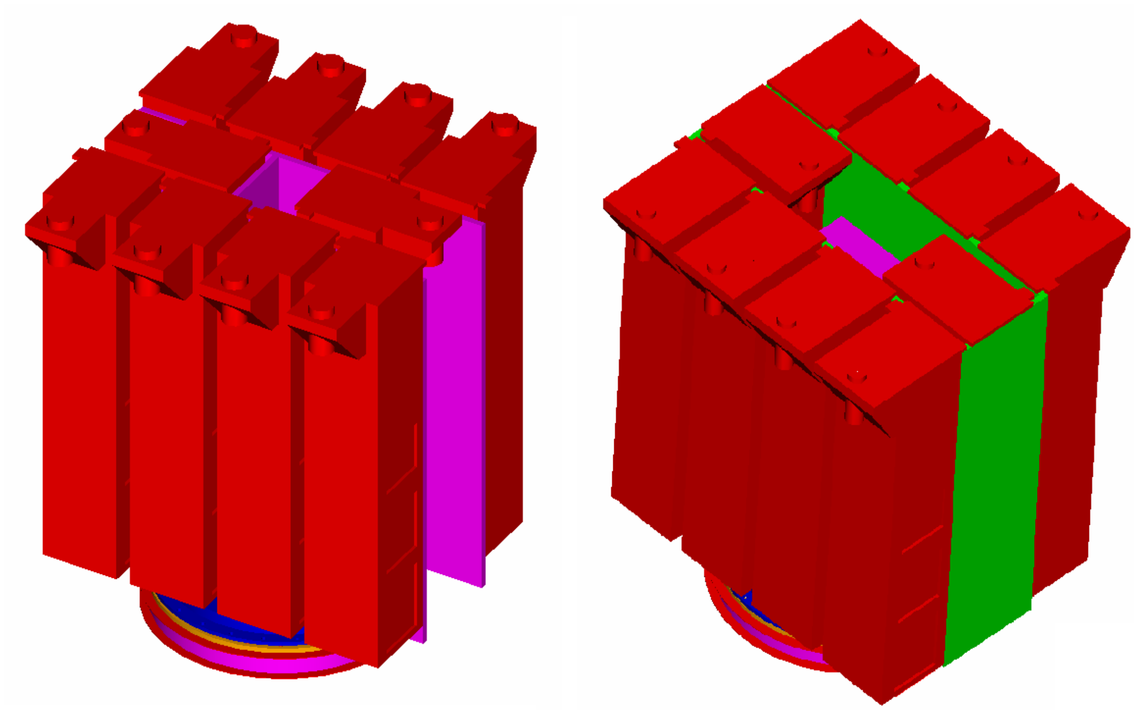

Figure 14. Loaded H Structure (Left) and Loaded D Structure (Right) from [15].

Another consideration to having the doors open inside is that they could contact other parts of the NPSCuL even if the center P-PODs had already deployed their payloads, therefore the outer P-PODs would require door stops. To prevent the opened P-POD doors from blocking the opening of the P-PODs in the center would require a specific opening sequence. Although this

configuration is simple it was complicated operationally since the order in which the P-PODs opened became paramount, , however by opening P-PODs to the outside there would be no restriction to their firing order, and no added complication to the structure.

4 The Box Structure. The box structure, as shown in the Figure 15 below, was a simple box with P-PODs mounted to each of its walls. P-PODs would be mounted in the same orientation as with the H and D structures, except that each P-POD would be swiveled 180 degrees so that it opened with its doors swinging to the outside. The box structure mitigated the problems with the H and D structures since it prevented any sequence restrictions and also prevented the P-POD doors from colliding with or blocking other parts of the NPSCuL. The box design, on the other hand, was more massive than the H or D structures and would put a fully loaded NPSCuL much closer to the 400 lb ESPA mass limit [15]. It would also make it more difficult for the NPSCuL to act as a mass simulator for lighter SPLs.

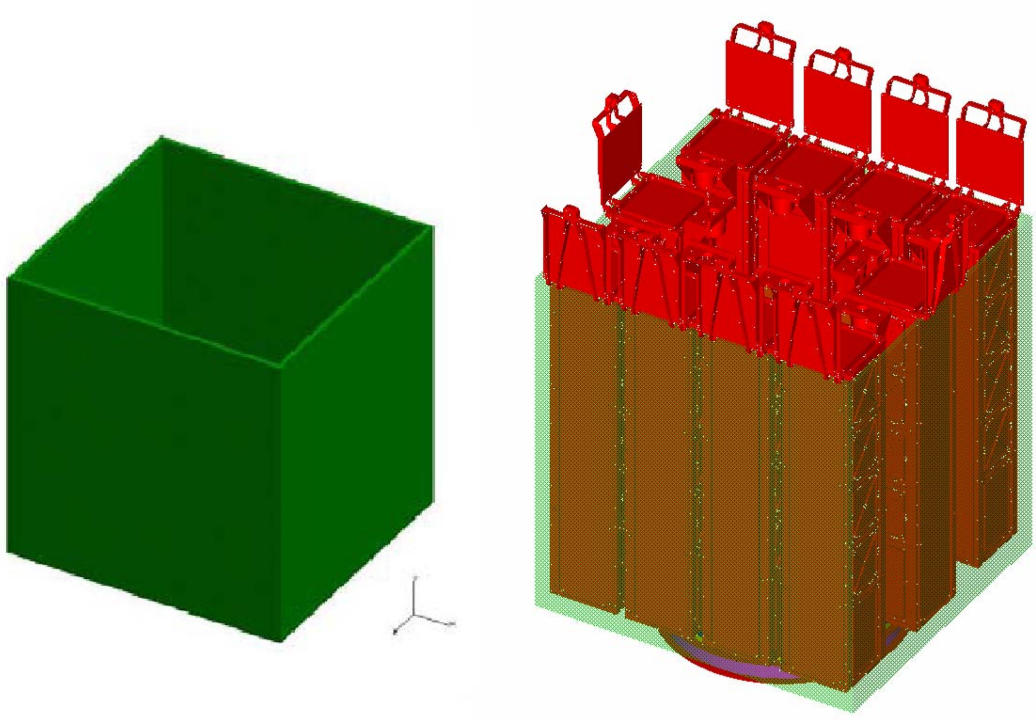

Figure 15. The Box Structure Empty (Left) and Loaded (Right) from [15]

5 The Advanced-D Structure:

In his thesis, Felix Rossberg then proposed the Advanced-D structure, which would allow the P-PODs to open to the outside, like in the box structure, but would be less massive than the box structure. The Advanced-D structure was a modification of the D-structure with the outside walls extended outward to allow the P-PODs to be swiveled and face inward, and opening to the outside. The Advanced-D was only slightly more massive than the D-structure, but much less than the box structure [15]. The Advanced-D was the final choice for NPSCuL since the design seemed to take advantage of the best of the H, D and Box structures with none of the weaknesses they had presented.

Figure 16. The Advanced-D Structure, the final NPSCuL Design

b. Lightband

Planetary Systems Corp. builds a device known as a “Lightband.” Lightbands come in various sizes and are designed to separate a payload from the launch vehicle. When using a Lightband, payloads will attach to the launch vehicle via the Lightband. The basic construction of a Lightband includes two connected rings capable of separation from each other on command from the launch vehicle. One ring is attached to the launch vehicle, while the other is attached to the payload; separations of the Lightband rings deploy the payload from the launch vehicle. [16].

In most cases NPSCuL should not require separation from the LV. The P-PODs would deploy the CubeSats and the NPSCuL and empty P-PODs could remain fixed to the ESPA or LV after deployment. If the PPL required separation of the NPSCuL and P-PODs from the ESPA, perhaps to reduce mass

before firing the 3rd stage, a Lightband could be used to jettison the empty NPSCuL and attached P-PODs once CubeSats have been deployed.

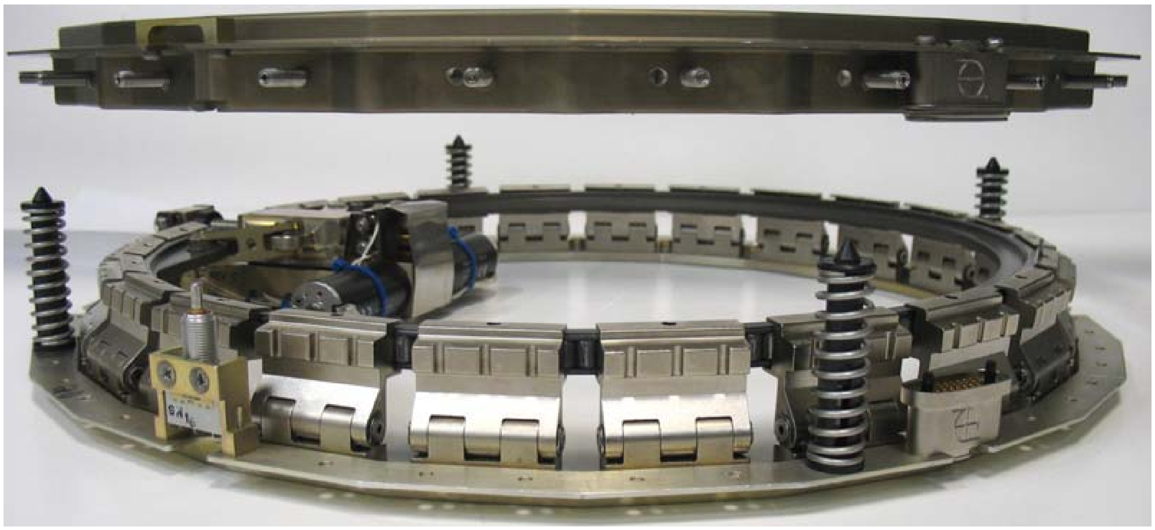

Figure 17. 15 inch Motorized Lightband Deployed from [16]

c. Sequencer and Battery

The P-PODs must receive the proper signal, either directly from the launch vehicle or from some other source in order to deploy. Although unlikely, if a launch vehicle is capable of providing ten distinct, time delayed signals, then the launch vehicle can deploy each P-POD individually at the proper time in orbit; this case would not require a sequencer or battery. If the launch provider is unable to provide ten distinct deployment signals, a single deployment signal can be sent to an NPSCuL sequencer, which would begin to deploy each P-POD in a pre-determined order and time interval. The sequencer may also include an onboard battery to provide enough power to operate each P-POD deployment mechanism. If a sequencer and battery are required, they could be located in the void between the inner two P-PODs or external to NPSCuL.

d. CubeSat Deployment from NPSCuL

The time at which NPSCuL and the other SPLs will deploy from the launch vehicle varies greatly by mission type and requirements. Additionally, the on-orbit operations vary depending on the type of launch vehicle. All Atlas and Delta launch vehicles use a liquid propelled final stage, which is capable of starting and stopping multiple times as necessary to insert the primary payload into its intended orbit. On some missions, if only carrying a PPL, the final stage may have significant propellant remaining (sometimes called "excess performance" in the Aerospace community) after completing all necessary operations for the PPL. These missions may be good candidate missions to carry SPLs since this excess performance can be used to lift and deploy SPLs without significantly increasing the cost of the mission.

The exact deployment time is heavily dependant on the operations necessary to insert the PPL into its required orbit, and the following are examples of when SPL might typically be deployed. If the PPL is headed to Geosynchronous Orbit, the SPLs and NPSCuL may deploy during the coast phase following initial insertion into Low Earth Orbit (LEO). In this case, SPL's would be deployed while the PPL is still present, after which the launch vehicle would re-start and conduct operations necessary to insert the PPL into it's required orbit. If the PPL is headed to LEO, the launch vehicle may first complete all operations necessary to deploy the PPL into its required orbit after which the launch vehicle may then transport itself and SPLs away from the vicinity of the PPL at which point the SPLs may be deployed.

The CubeSats should be deployed while the NPSCuL is still attached to the ESPA or LV. While still attached to the ESPA, the NPSCuL can guarantee all CubeSats are deployed away from the LV and other payloads since it would be physically impossible to do otherwise. If the NPSCuL were detached from the ESPA before deployment of the CubeSats with the intent to deploy CubeSats afterwards, the tumbling NPSCuL could deploy CubeSats in the direction of the LV. With that being said, at some point in the future an NPSCuL

could be designed with attitude control, which might allow for more flexibility, including the ability to safely deploy CubeSats after NPSCuL had separated from the LV.

e. 3U, 5U and 6U P-POD Versatility.

The NPSCuL design can accommodate a variety of P-POD sizes. As mentioned earlier, the 3U P-POD is currently the only flight-proven P-POD. The 6U NASA Ames "six pack" is being developed but not yet flown. Because the 3U and 6U P-PODs are only 17" in length it has been proposed that a 5U P-POD, at a length of about 28", would make better use of the entire NPSCuL volume. For now, the 5U P-POD remains only a concept, but could be developed at any time. NPSCuL has 10 slots for P-PODs, which could accommodate all types in existence and those that have been proposed for the future (5U and 6U). The 6U P-POD would use two slots, since they are twice the width of a 3U. When using only 3U and/or 6U P-PODs, NPSCuL would have a 30U capacity. With 5U P-PODs, NPSCuL capacity would increase to 50U.

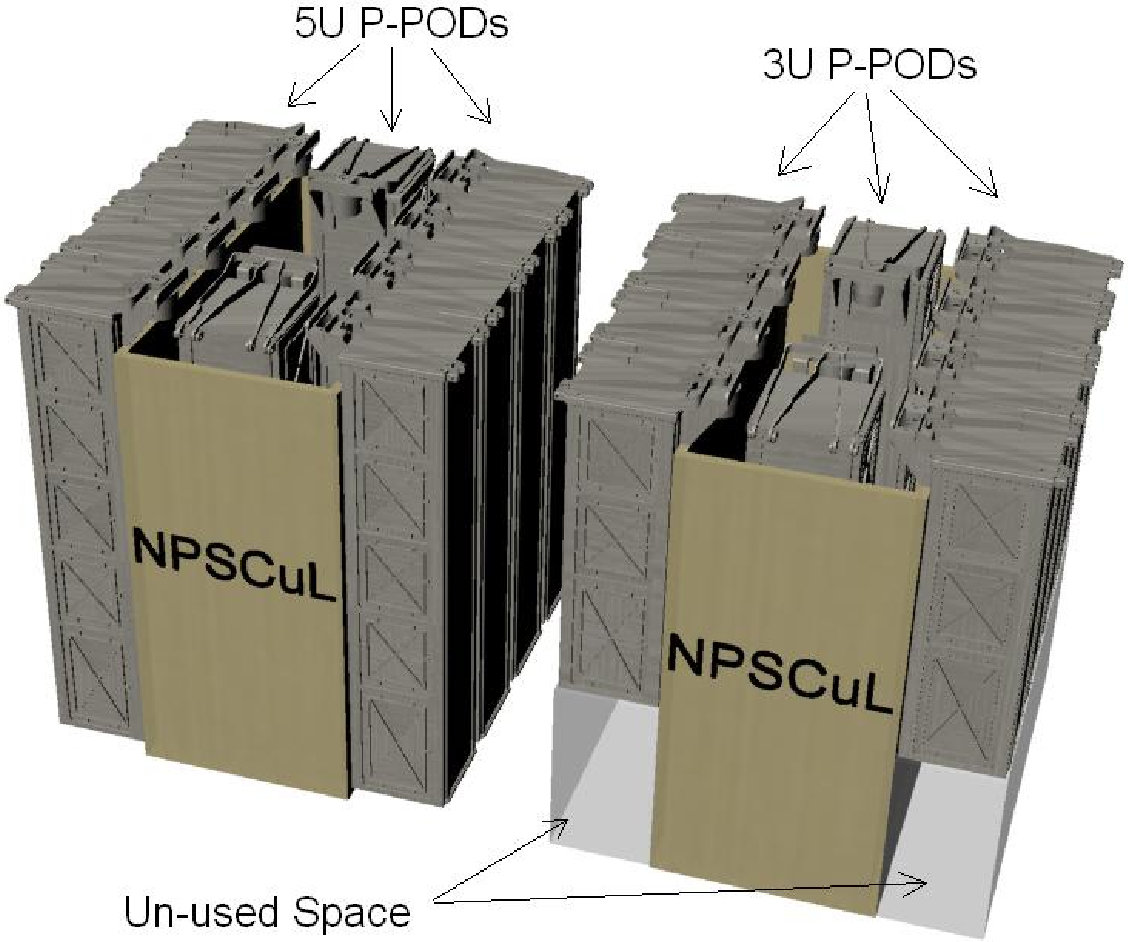

Figure 18. NPSCuL with 5U P-PODs (Left) and 3U P-PODs (Right).

D. NPSCUL AS A MANIFESTED PAYLOAD

Although the original idea for NPSCuL was to provide a functional mass simulator for flights when other manifested payloads failed to make launch, NPSCuL may be even more useful as a manifested payload. As it will be discussed in the next section, as a mass simulator NPSCuL must match the mass and CG properties of the payload it is replacing. It may be difficult to use the full NPSCuL CubeSat capacity and also meet the mass and CG required as a mass simulator. When freed from the constraints of a mass simulator NPSCuL could be used to its full CubeSat launch capacity.

The mass and CG properties of a fully loaded NPSCuL depend on which types of P-POD are used. Table 1. is a simplified mass budget, including CG properties for each component and overall CG.

NPSCuL Simplified 3U and 5U Mass Budget with CG						
			3U P-PODs		5U P-PODs	
Component	Mass (lbs [kg])	Num	Total (lbs [kg])	CG (inches mm])	Total (lbs [kg])	CG (inches [mm])
Lightband	5.6 [2.5]	1	5.6 [2.5]	1.05 [27]	5.6 [2.5]	1.05 [27]
NPSCuL	89.4 [40.6]	1	89.4 [40.6]	11.40 [290]	89.4 [40.6]	11.40 [290]
3U P-PODs	5.8 [2.6]	10	57.5 [26.1]	21.93 [557]		
3U CubeSats	6.6 [3.0]	10	66.1 [30.0]	21.33 [542]		
5U P-PODs	8.0 [3.6]	10			80.00 [36.3]	19.93 [506]
5U CubeSats	11.0 [5.0]	10			110.2 [50.0]	17.39 [442]
Sequencer	13.0 [5.9]	1	13.0 [5.9]	3.69 [94]	13.0 [5.9]	3.69 [94]
Total			**231.5 [105]**	**16.2 [411]**	**298.2 [135.5]**	**15.4 [391]**

Table 1. NPSCuL Simplified 3U and 5U Mass Budget with CG. Mass numbers from [1], [3], and [15]. 5U P-POD and Sequencer masses are estimated.

Table 1. describes the mass and CG characteristics of an NPSCuL loaded with ten 3U or 5U P-PODs. Some assumptions were made in this mass budget, namely:

1. CubeSats are 2.2 lbs (1 kg) per “U”.
2. Either a 15” Lightband or an equivalent non-separating adapter with nearly identical mass and size characteristics to a Lightband is used.
3. All CG calculations assume the NPSCuL is offset 2.1” from the SSIP to account for the Lightband or equivalent non-separating adapter.
4. A sequencer weighs 13 lbs (6 kg), is two inches thick, the CG is at the center, and is placed on the NPSCuL base plate. The sequencer has not yet been designed, so this may be a rough estimate.

Even if some of the above assumptions were to prove inaccurate, it can be seen that the natural CG for NPSCuL is almost four inches from the 20” limit and probably more since payloads lighter than 400 lbs can exceed the 20” limit as described in Figure 10 Even with the mass estimated on some components, NPSCuL is not in danger of exceeding the ESPA mass or CG limits.

Although the ESPA ring is capable of carrying up to 400 lbs per slot, there may not necessarily be enough mass margin available to fill each ESPA slot, and the slots filled might be allotted less than 400 lbs. In this situation NPSCuL has a major advantage over competing payloads. Unlike most satellites, NPSCuL can also be lighter than the full mass described in Table 1. since it does not need to launch with a full CubeSat payload. Although technically NPSCuL could launch with as few as one P-POD, at some point it seems that it would be impractical to launch with fewer than some number of P-PODs. Assuming it was decided that it would be worth launching NPSCuL as long as it carried at least 4 full P-PODs (12U worth of CubeSat volume) then the total NPSCuL payload mass could be as low as 151 lbs. This is a useful feature since NPSCuL could still launch with less mass and a partial CubeSat payload rather than not launching at all.

E. NPSCUL-LITE

While writing this thesis, development of a new NPSCuL type concept began, called “NPSCuL-Lite.” The new concept was developed specifically for a new secondary payload adapter called the “Aft Bulkhead Carrier” (ABC), which has lower mass limits and different payload volume constraints. It was proposed to NPS by a party interested in NPSCuL, but recognizing the original design would not work with the new adapter. Although designed for the ABC, NPSCuL-Lite is still compatible with the ESPA. The NPSCuL-Lite can carry up to eight 3U P-PODs (it is not compatible with 5U P-PODs). The NPSCuL-Lite structure is lighter than the standard NPSCuL, therefore it may be practical to substitute the NPSCuL-Lite for the full NPSCuL on an ESPA launch if the launch has more restrictive mass limits than the normal ESPA mass capacity, or if NPSCuL is not

yet available. NPSCuL-Lite is a variation of the Standard NPSCuL “Box” Design. As it is currently designed the ABC will accommodate a 170 lb payload in an irregularly shaped payload volume. Since the development is still in progress, some of the specific design details and requirements are still to be determined and may change from previously stated numbers.

Although the ESPA standard interface plane (SSIP) is specific to the ESPA ring to avoid confusion the SSIP right-handed coordinate system will be used when describing NPSCuL-Lite in the same way it was used with NPSCuL (There is no equivalent ABC interface plane since the ABC user guide as not yet been released). NPSCuL-Lite uses a design similar to the NPSCuL Box design. Eight 3U P-PODs are most efficiently arranged in a pinwheel fashion with each group of two P-PODs 90 degrees relative to the next group about the x-axis (relative to the SSIP). Since 3U P-PODs should be about the same size as one 6U P-POD it may be possible to accommodate 6U P-PODs on NPSCuL-Lite using two slots at a time.

When looking at the volume alone, it’s possible to fit 5U P-PODs, however, loaded 5U P-PODs are approximately 19 lbs. each, compared with only 12 lbs. for 3U adding a total of 56 lbs. mass (for eight P-PODS) in addition to any structural mass that may be necessary to accommodate the longer 5U P-PODs. The additional mass for 5U P-PODs would put NPSCuL over the mass limit for the ABC adapter, even with significant mass optimization; it would be very difficult to accommodate 5U P-PODs. Table 2. is a summary of the NPSCuL-Lite mass budget with 3U P-PODs.

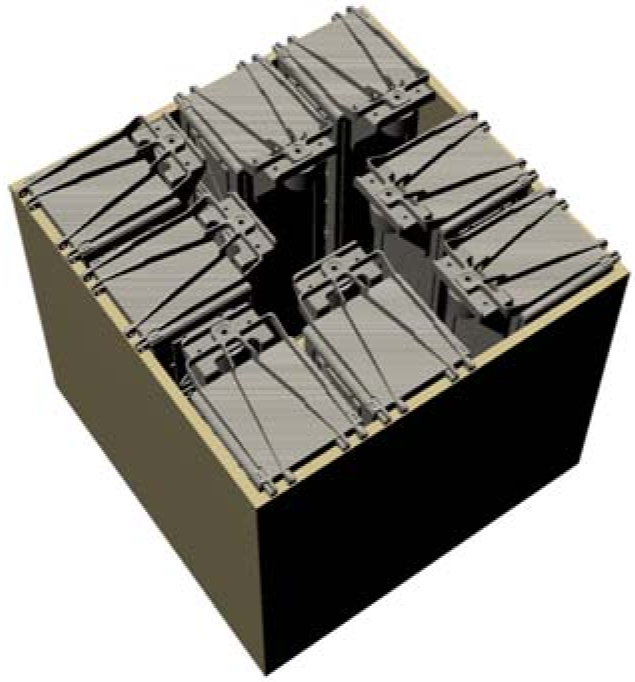

Figure 19. NPSCuL-Lite

0.25 inch (1/4 inches) Sidewall Thickness					
	Weight (kg)	Weight (lbs)	Num	Total (kg)	Total (lbs)
3U P-PODs	2.60	5.73	8.00	20.8	45.9
CubeSats	1.00	2.21	24.00	24.0	52.9
Sequencer	3.00	6.62	1.00	3.0	6.6
Assembly Hardware	0.68	1.50	1.00	0.7	1.5
Structure	17.82	39.29	1.00	17.8	39.3
Total				**66**	**146**
Mass Margin				24	54
% Mass Margin				14%	

Table 2. NPSCuL-Lite Preliminary Mass Budget

Most of the discussions found in this thesis apply to both the NPSCuL and the NPSCuL-Lite. Obviously technical details are specific for each adapter; the NPSCuL is compatible only with the ESPA ring while the NPSCuL-Lite is compatible with the ESPA, ABC and possibly other adapters in development.

F. NPSCUL AS A FUNCTIONAL MASS SIMULATOR

1. Operations as a Mass Simulator

Although implementing NPSCuL as a mass simulator or “hot standby” would certainly be challenging, it could be achievable. As a backup payload, it would almost certainly need CubeSats and P-PODs built, tested, and on standby, ready for integration onto an NPSCuL with short notice. There may not be enough time to announce the launch, select CubeSats for launch, develop, and build the CubeSats as expected for a manifested NPSCuL launch. This may be possible if a ready-to-go queue of CubeSats were already built and populated, allowing for such an efficient system. CubeSats would be in a flight-ready status whether they are physically located at NPS or at the location of development. If it were announced early enough that NPSCuL had been selected as a “hot standby” for a given flight, the flight-ready CubeSats could be shipped to NPS or Cal Poly (their respective integration authority) for integration onto P-PODs. A system of this type would almost certainly require a fairly high number of launches and CubeSat developers to support it. If there are too few CubeSats or P-PODs ready for launch at any given time, this idea although novel would be useless since it wouldn’t be ready in time for launch. For success with this process model, CubeSat developers must have the faith that although they may not yet have a specific launch date, they know that as long as they are manifested in the NPSCuL launch queue, it is only a matter of time until NPSCuL is launched either as a back-up to a manifested SPL or as a manifested payload.

Since NPSCuL can carry P-PODs in a variety of slots, can leave some slots empty, or can carry additional ballast, the mass can be increased or decreased and the CG can be adjusted from its natural location.

The limits to which NPSCuL is mass and CG configurable should be adequate to facilitate replacement for most secondary payloads. In general, if a payload is very light, or has a CG in an extreme location NPSCuL may not be an acceptable substitute, but this should be the exception rather than the rule.

The mass configurability of NPSCuL is between a minimum of 92 lbs (42 kg), and a maximum of 400 lbs (181 kg). The lower limit assumes an NPSCuL structure is 74 lbs. (34 kg) and a fully loaded 3U P-POD is 12 lbs. (5.5 kg), and a Lightband or solid 15" connector is 6 lbs (2.7 kg) with no sequencer or battery onboard. The maximum would require nearly 100 lbs. of ballast in addition to a full load of 5U P-PODs. If each CubeSat weights 1 kg per 1U as specified in the CDS, loaded 3U, 5U, and 6U P-PODs should weigh approximately 12 lbs. (5.5 kg), 19 lbs. (8.5 kg), and 24 lbs. (11 kg) respectively. NPSCuL is configurable in any mass increment, not just in 12, 19 or 24 lbs. increments, since ballast may be loaded and can be built to nearly any mass required.

The envelope in which the NPSCuL CG is configurable is much more complicated to explain than the mass envelope. When referring the location of the center of gravity in the X, Y or Z direction, the nomenclature "CGx", "CGy", "CGz", will be used respectively. Additionally, unless otherwise stated, CGx, CGy and CGz will always be with respect to the SSIP. At full load (400 lbs.) CGx must be within 20" of the SSIP, CGx may be up to 30" from the SSIP with less mass however (see Figure 10.). The NPSCuL center of gravity is configurable in all 3 directions: x, y and z. However, the extent to which it is configurable is a function of the total mass limit, and the direction in which the CG must be moved from its natural position.

The NPSCuL P-POD slots have been numbered 1 through 10 in a fashion similar to a 10 hour clock. Beginning with the P-POD exactly to the right of the top center P-POD (top meaning the +Y direction in the SSIP, the direction of travel), the P-PODs are numbered sequentially in a clock-wise manner. Figure 20 depicts the NPSCuL with the numbered P-PODs projected onto the SSIP.

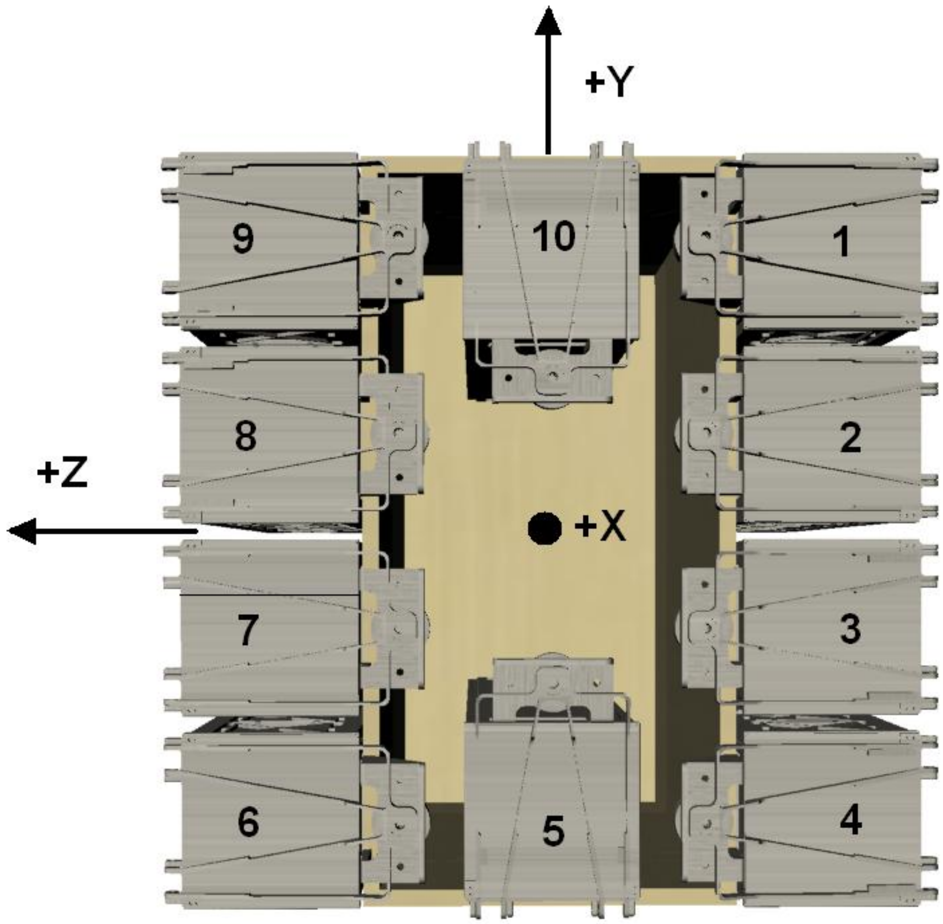

Figure 20. NPSCuL Projected onto the SSIP with P-POD Numbering

2. NPSCuL CG Configurability

In general, the center of gravity for a manifested secondary payload would be very close to zero in the y and z directions, but may vary in the x direction. This makes the x direction the most important direction in which to be able to shift the CG, however the only way to move the CG for NPSCuL in the x-direction is by adding ballast, by removing CubeSats, or removing entire P-PODs.

The NPSCuL Structure, 15” ESPA adapter and sequencer have a natural CGx of about 10” without any payload. Loaded 3U P-PODs have a natural CGx of 21.6”, and loaded 5U P-PODs have a CGx of 17.9”. These P-POD CGx calculations assume each 1U CubeSat volume is loaded with 1 kg of CubeSat payload or equivalent, these CGx figures do not change much. Since loaded P-

PODs have a relatively high CGx, while all remaining NPSCuL parts have a low CGx at around 10”, if P-PODs are removed to lighten the overall payload this causes a corresponding shift in CGx in the negative x-direction. Ballast can be attached to NPSCuL at almost any point in the x-direction between 3.6” and 22.3” from the SSIP. At the low end, 3.6” is far from the 21.6” CGx of loaded 3U P-PODs, therefore removing a P-POD and replacing it with ballast close to the base of NPSCuL (3.6”) causes a CGx shift of almost one inch toward the SSIP. On the other hand since a 3U P-POD has a CGx at 21.6” while the furthest point from the SSIP at which ballast can be attached is at 22.3” from the SSIP, removing a P-POD and replacing it with ballast (at 22.3”) will only raise CGx by three-hundredths of an inch.

If a secondary payload failed to make its flight, and NPSCuL is to replace the payload as a functional mass simulator, it is assumed that CGy and CGz should be zero, while the mass and CGx must match the original payload. The extent to which NPSCuL is configurable, is a function of three variables: mass, CGx, and payload capacity. It is also assumed that NPSCuL should always use the maximum payload capacity possible, so question is “what is the maximum payload capacity at which NPSCuL could still match a given mass and CGx of another payload?” Figure 21 and Figure 22 below depict the CGx envelope given NPSCuL is to act as a 250 lbs and 400 lbs. mass simulator respectively. These figures show the CGx envelope using 3U P-PODs with the given mass, the exact envelope is payload specific, so these figures are only examples based on the assumptions listed above. By comparing Figure 21 and Figure 22, it can be seen that the CGx envelope is larger for the heavier 400 lbs. case. As a 400 lbs mass simulator NPSCuL must have more ballast loaded than for lighter cases, and since ballast can be loaded anywhere between 3.6” and 22.3” from the SSIP, the result is a larger CGx envelope. Graphs such as these are useful since one can quickly determine the maximum capacity at which NPSCuL is

useful as a mass simulator. For example, by looking at Figure 21 one can quickly see that using 3U P-PODs, as a 250 lbs. mass simulator with a CGx of 12”, the maximum capacity would be limited to 18 CubeSats.

There are also differences between 3U and 5U P-PODs since 5U P-PODs naturally have a lower CGx than loaded 3U P-PODs. Neither 3U nor 5U P-PODs are better than the other in every situation. 5U P-PODs are generally less limiting to the CubeSat payload volume if a low CGx is required, but more limiting to the CubeSat capacity when a high CGx is required. Notice if NPSCuL is used as 250 lbs. Mass Simulator with a CGx of 12”, when using 3U P-PODs (Figure 21) the capacity is limited to a capacity of 18U, but when using 5U P-PODs the capacity would be limited to 25U. Conversely, given the same 250 lbs. mass limit with a higher CGx such as 16”, an NPSCuL loaded with 3U P-PODs accommodate a volume of 30U, but if using 5U P-PODs a volume of only 15U is possible.

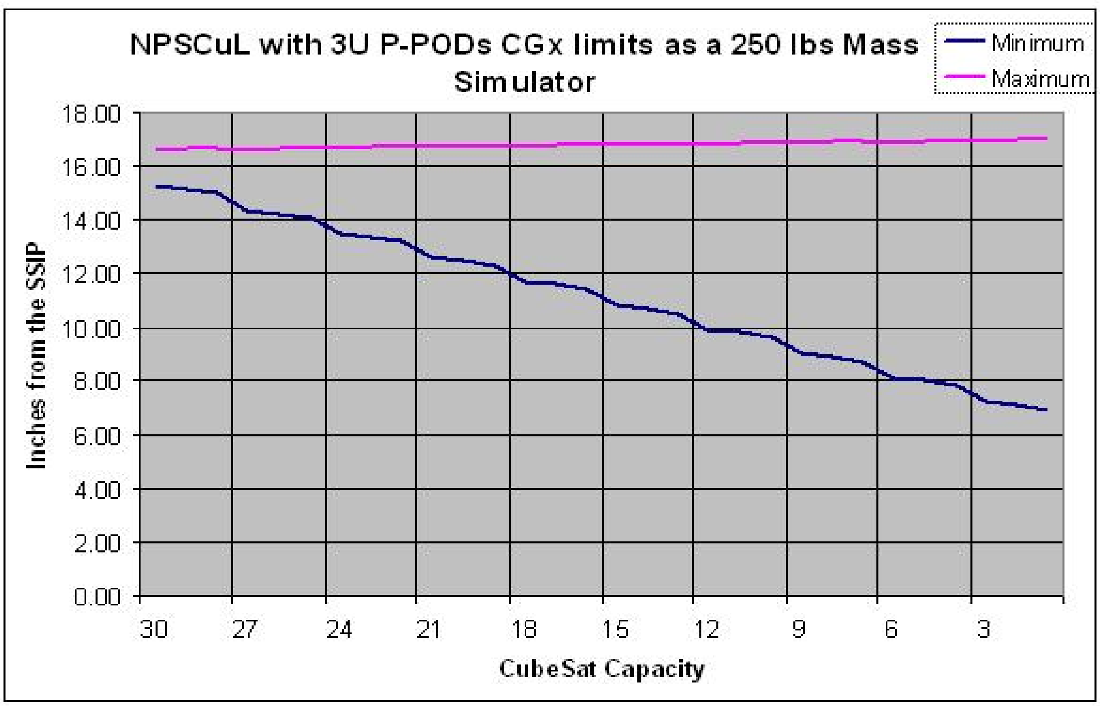

Figure 21. NPSCuL CGx Envelope as a 250 lb Mass Simulator

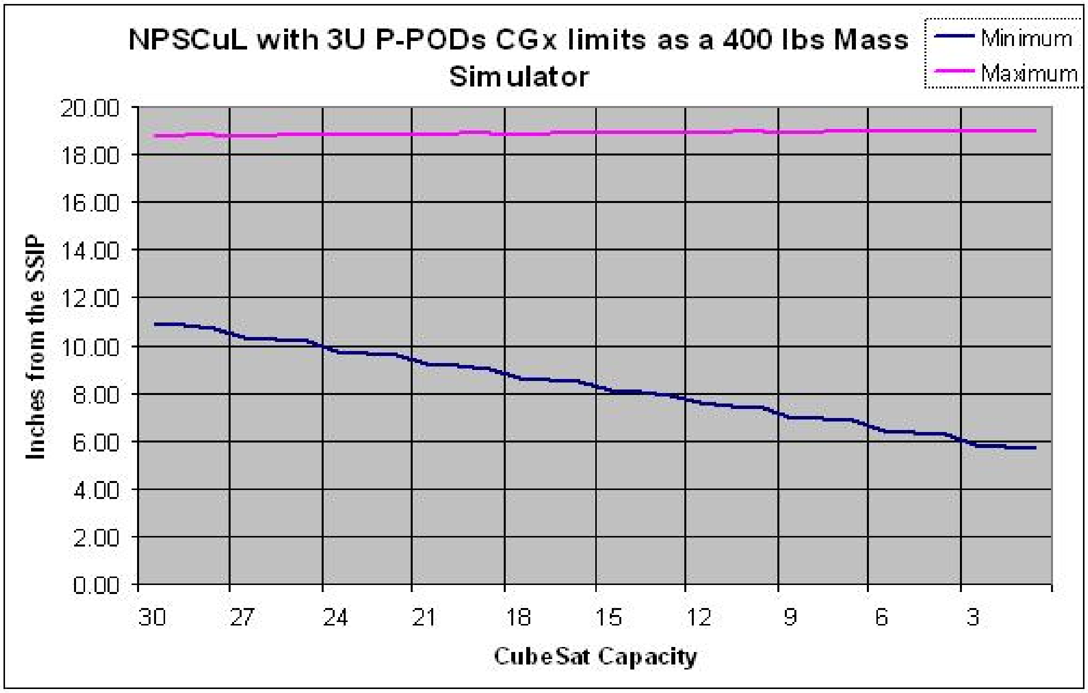

Figure 22. NPSCuL CGx Envelope as a 400 lbs Mass Simulator

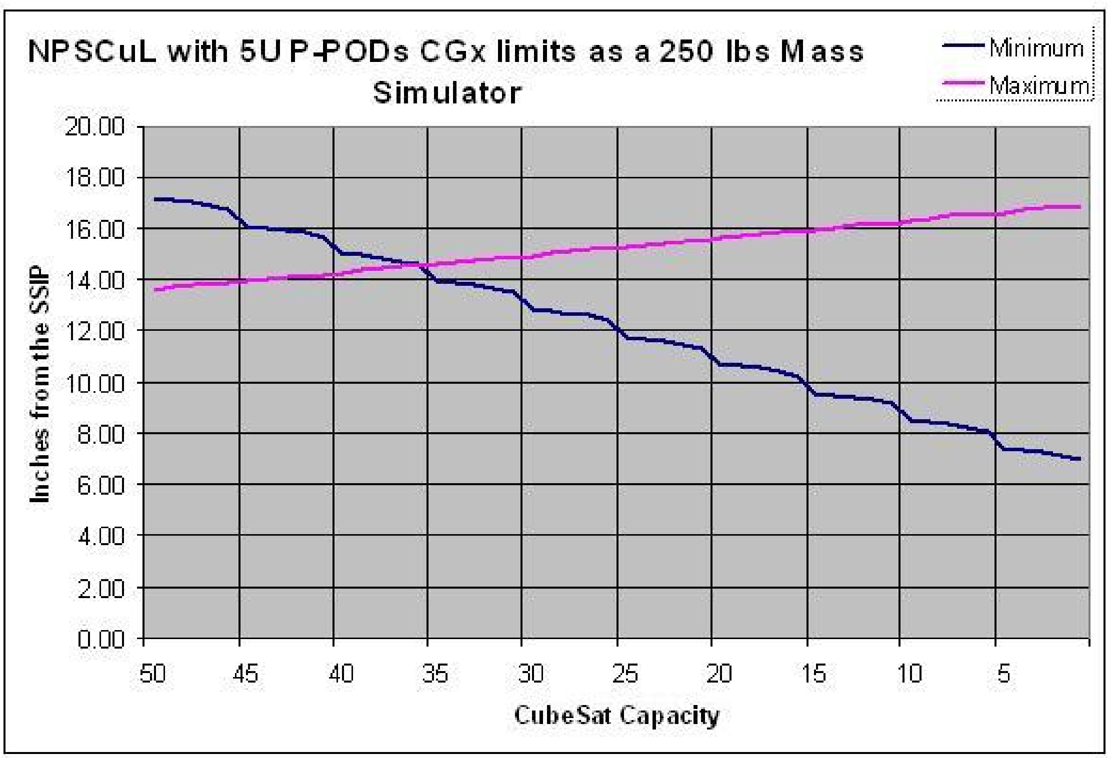

Figure 23. NPSCuL with 5U P-PODs as a 250 lbs Mass Simulator

G. THE PROCESS AND REQUIREMENTS DOCUMENT

The NPSCuL Process and Requirements document (PRD) was written in conjunction with this thesis and was one of the two deliverables due to CSEWI as part of the grant received. This section discusses the development of the PRD, which can be found in Appendix F.

1. PRD Summary

When NPSCuL is manifested to launch on a government launch vehicle the entire NPSCuL capacity may not be used by government or DoD CubeSat payloads. This is an excellent opportunity to allow colleges, universities and others to launch CubeSats of national, scientific, educational or commercial interest on a space-available basis. This could be the first domestic launch of non-government satellites in the United States; at the time of publication only NASA has launched CubeSats domestically. Over 50% of all CubeSats have been built by U.S. developers and until today, with the exception of NASA, they have been forced to find launches overseas.

The process in the NPSCuL PRD has the primary aim to allow for space-available NPSCuL CubeSat launches. One goal of the process was to allow space-available launch on NPSCuL with few requirements not already listed in the CDS. The process requires parties, to develop a CubeSat according to the CDS that serves some national, scientific, educational or commercial purpose and fill out a questionnaire to be added to a list of CubeSats called the NPSCuL CubeSat Queue (NCQ). The NCQ is a sequential list ordered on a first-come first- serve basis.

When NPSCuL is selected for flight, the program office would inform NPS of the number of space available slots on NPSCuL that would be available for non-government CubeSats. The NPSCuL team at NPS would then select appropriate CubeSats, as defined by the PRD from the NCQ, including back-up CubeSats, and present the list to the program office for approval. In order for CubeSats to be selected from the NPQ, they must be flight-ready within the

necessary timeframe and their orbital requirements must match flight orbital parameters. The program office would have the ultimate authority to approve or change the rideshare manifest list.

Once the manifested CubeSat list is approved by the program office, NPS would make all necessary arrangements for the NPSCuL structure. The NPS SSAG would appoint a Flight Coordinator who would be responsible for all communication with the various CubeSat developers and for coordination between the CubeSats and the launch provider or program office. This could be an SSAG master's thesis student who could write a thesis on the programmatics of coordinating space flight rideshare opportunities among so many participants.

The Process and Requirements Document will change and be revised, as necessary each year, as the process is refined; the version submitted with this thesis is a starting point. The author realizes the aggressive nature of the Process and Requirements Document that, if implemented, would place NPS at the forefront of the CubeSat community, possibly as the premier U.S. CubeSat launch provider in the near future.

2. Development of the NPSCuL Process and Requirement Document

There were other processes used as examples for the process recommended in the first version of the PRD. The primary process, used as a reference by the author, was that of the DoD Space Experiments Review Board (SERB). The SERB meets annually and prospective payload developers may present their experiment to the board, which ranks each experiment on a list, unless removed from consideration. The Space Test Program (STP) administers the SERB process for the DoD, which provides opportunities to DoD-sponsored payloads to launch on various (typically DoD) launch vehicles on a space-available basis. When a compatible mission is identified to included STP secondary payloads, experiments are chosen from the list already produced by the SERB.

One of the preliminary versions of the NPSCuL PRD included a process where prospective CubeSat experiments would be presented to a board at NPS and ranked similar to the process used by the DoD SERB. There were arguments both for and against this type of a selection process. The arguments for the process included:

- The process could identify CubeSats, which would be useful to U.S. National or DoD interests.
- Student could participate in the process providing valuable training to NPS Student officers.
- A ranking system may promote development of more sophisticated or interesting experiments since these experiments would most likely be given a higher ranking on the NCQ.

Arguments against the process include:

- There may be fewer interested parties than necessary to fill all of the available slots making any type of ranking system un-necessary.
- The process would be time consuming for members of the SSAG at NPS.
- A ranking type system could be implemented in the future if a first-come-first-serve type system became inadequate.

In the end, it was decided not to recommend a ranking style system at this time. The main reasoning behind the decision was essentially that a first-come first-serve style list was comparatively easy to implement, and it does not preclude changing to a ranking style system in the future, if it becomes necessary. Although CubeSats would not be ranked by merit, there should be minimum criteria that CubeSat experiments must meet in order to be added to the NCQ, which is discussed in the following section.

3. CubeSat Requirements for NPSCuL Space-Available Launch

It was important from the beginning to keep requirements for flight on NPSCuL consistent with those required for any CubeSat launch. In many cases,

CubeSat developers do not know how they will launch their CubeSat before they begin development, therefore the CDS becomes the one common requirement standard between all CubeSats. Additional requirement were difficult to determine for the first revision on the PRD for various reasons. NPSCuL and NPSCuL-Lite are compatible with the ESPA, but may also be compatible with other secondary payload adapters, some of which are still in development. Requirements for launch on the ESPA can be found in the DoD Space Test Program Secondary Payload Planner's Guide (ESPA PPG), but those requirements may differ from the other Secondary Adapters for which the payload planner's guides have not yet been released. Primary payloads may also impose additional requirements on secondary payloads on a mission unique basis. As a result the first version of the NPSCuL PRD included few specific design requirements outside the CDS, which should be enough to satisfy most requirements for the various secondary payload adapters. As more information about these adapters becomes available the PRD should be updated with more specific launch environment related requirements.

Other than design and launch environment related requirements, to guarantee the space on NPSCuL is used for worthwhile experiments, developers are required to demonstrate their experiment serves some national, scientific or educational purpose. For example, using CubeSats to do nothing more than launch ashes into space would probably not be accepted for space-available flight on NPSCuL. The PRD also states that CubeSat should have some ability to communicate with a ground station; this requirement could be waived if it can be shown that a CubeSat can perform a worthwhile mission without ground communications.

4. Conclusion to PRD Discussion

The first version of the PRD will most likely be changed especially following the lessons learned on the first NPSCuL launch with slots for space-available CubeSats. As it currently stands, it is merely a *proposed* process for

manifesting CubeSats for space-available launch and will probably not be accepted officially by the DoD, STP or CubeSat launch communities, until after the first NPSCuL launch including space-available CubeSats.

III. NPSCUL STUDY, FUNDING AND DELIVERABLES

A. FUNDING AND DELIVERABLES

The CSEWI sponsored the NPSCuL project during the 2007 fiscal year with a grant for $20,000. The agreement between NPS and CSEWI is outlined in a Navy Cooperative Research and Development Agreement (CRADA). The CRADA includes a Statement of Work, which obligates NPS to produce certain deliverables [11].

The following deliverables found in the statement of work are the responsibility of NPS [11]

1. Develop and deliver a CubeSat Launcher Process and Requirements Document.
2. Design and construct a prototype hardware mock-up of a CubeSat launcher. Such a launcher would comprise multiple P-PODs embedded in an ESPA sized payload volume.

The two deliverables outlined above were the primary tasks for this thesis. The second deliverable, the prototype hardware mock-up, was especially involved and the details are outlined in the following section.

B. CONSTRUCTION OF THE NPSCUL HARDWARE MOCK-UP

1. Size

As stated above, part of the agreement with CSEWI and one of the deliverables was to build a functional prototype for demonstration purposes. The first consideration for this prototype was the size. At a size that almost completely fills the ESPA launch envelope (24” x 28” x 38”), a full 1 to 1 scale model is too large. This could easily be transported to various conferences and functions in a van or truck, but it would be difficult to carry a model of this size in the trunk of a car or on an airplane. The group did consider that the P-PODs could be removable, but even then the model was still a fairly significant volume

for more restrictive types of transportation. It was decided to make the model smaller than 1 to 1. However, neither should the model be too small. CubeSats are only 10 cm per side and, if made it too small, the model may not have enough fidelity to adequately demonstrate the concept. At ¼ scale for instance the size would now be 6" x 7" x 9", this is roughly the size of a very thick laptop computer. Although ¼ scale model would be easy to transport, unfortunately it would be so small that the model CubeSats would be about the size of a game die.

It was decided that ½ scale was the best scale for a functional demonstration model. The exact dimensions of the NPSCuL, not including P-PODs, at half scale are 11.8" x 11.2" x 5.6"–small enough for air transport or car, yet still large enough to have a high amount of visual impact and detail for demonstration goals.

2. NPSCuL Mock-up Construction

There are essentially three parts to the NPSCuL functional demonstration model: the NPSCuL adapter, the P-POD models, and the electronic circuitry necessary to open the P-POD doors.

Fortunately, the design for the NPSCuL is quite simple, which made the choice of material for construction straightforward. Several materials were considered including polycarbonate, aluminum 7075, aluminum 5056 and ABS plastic. Polycarbonate was very easy to work with and could even be transparent, allowing observers to see inside the NPSCuL to better understand its construction and operation. ABS plastic could be built using a 3D printer and is an inexpensive material. Aluminum 7075 and 5056 would be more expensive and heavier, but both would have a more impressive appearance and look the most like actual flight hardware.

The ABS plastic and poly-carbonate options were eliminated because it would have an unimpressive appearance and certainly would not be up to the caliber CSEWI should expect for a $20,000 grant. Aluminum 7075 (aircraft grade

aluminum often used on spacecraft) was an attractive option for the model since it would be very realistic; the actual NPSCuL would most likely be constructed from this type of material. However, Aluminum 7075 is also expensive, difficult to machine and does not have an appearance that differs greatly from standard 5056. After speaking with the machinist at NPS, it was decided to first build a model out of polycarbonate to make a final evaluation of the design and make any last minute detail changes, after which the final model would be built from standard aluminum 5056.

There were a couple small design differences between the ½ scale model and an actual flight article. The flight article will have a wall thickness of 15mm or .59" inches, the ½ scale model used a ¼" wall thickness simply because it is readily available while 7.5mm is not. Additionally, due to the narrow wall thickness, the walls could not be joined directly using screws, so a bracket was used to join each wall in the inside of the NPSCuL. An anodyne, chemical conversion coating finish was applied for an authentic look.

3. P-POD Construction

The next step in construction of the model was to build the P-PODs. In order to demonstrate operation of the real NPSCuL, the model needed to have operable P-POD doors that could be opened in sequence. This posed a problem because of the level of detail needed to make P-PODs functional at half scale. The machinist could build P-PODs from Aluminum much like the NPSCuL model; however this was an impractical solution since it would take weeks or months for a machinist to build each P-POD with enough detail to look realistic.

Rapid prototyping (RP) is a good candidate for projects where high detail is required. Since there are several types of RP available, it required a good amount of research and education to determine the best prototyping method for this project as well as the best way to go about acquiring the services of an RP machine.

Some of the rapid prototyping methods researched and considered for this project were [19]:

- Selective Laser Sintering
- Fused Deposition Modeling (FDM), also called 3D printing (3DP)
- Stereo Lithography (SLA)
- Laminated Object Manufacturing
- Electron Beam Melting

Each of these technologies varies dramatically by materials used, price, speed, complexity, and resolution. Electron Beam Melting for instance is a very expensive technology that can manufacture high quality parts from various titanium alloys and typically requires a dedicated technician to run the machine. If price were no object, then EBM could have produced exceptional ½ scale titanium models for the functional NPSCuL model. FDM or 3DP, on the other hand, typically work with plastic and poly-carbonate materials and tend to be the least expensive of the RP technologies. 3DP can also be used with only minimal training. After looking into the details for each technology, it became apparent that the only technology that would fit within the budget was 3DP.

Despite the relatively low cost of 3DP when compared with other types of RP technology, they still produce high quality models. 3DP has become the most widely used RP technology, and is probably the only RP technology that has taken advantage of economies of scale in recent years enough to substantially drive down the cost while increasing performance. As a result, 3DP machines tend to produce products nearly on par with much more expensive RP technologies at a fraction of the cost. While only a few years ago the least expensive RP machines cost well over $100,000, today some commercially available 3DP machines retail for less than $20,000 such as the Dimension BST

768. It appears that 3DP has become popular enough in the mechanical engineering world that it is the default choice for most projects unless another form of RP is absolutely necessary.

In the past, the SSAG has contracted out to various companies to build 3D parts on 3DP machines. Although the SSAG didn't own an RP machine, a computer-aided drafting (CAD) file could be electronically sent to various companies who produced RP products for customers. The process of ordering RP parts online has become streamlined; today an engineer can go to dozens of websites and get instant quotes for any CAD file within minutes. After receiving a quote and paying, these companies can begin printing the prototype almost instantly and ship to the customer within days.

Figure 24 below is a screenshot capture from Xpress3D for a 1/2 scale 5U P-POD. The quotes range from $505 - $1,000 per unit. Assuming the cheapest available technology was used to build ten 5U half scale P-PODs the total would be at least $5,050. This was a problem since the budget for the model was about $8,000. Using this method would barely leave enough money for other important parts, the actual structure, and electronics necessary to operate the P-PODs doors. Additionally, the price would only hold true if only ten 5U P-PODs were built correctly the first time. Although this might fulfill the minimum requirements set for deliverables in the CSEWI/NPS CRADA, to fully demonstrate the versatility of the NPSCuL concept, it was preferred to produce several P-PODs including 3U, 6U and 5U. Like many engineering projects there are often re-designs or mistakes requiring rework, so it was impractical to plan on building only ten P-POD models.

	PRICE	SHIP	PROCESS	COMPANY	
SELECT	$834 - $959 Details	August 22	FDM	RedEye RPM	Build with REAL thermoplastics such as ABS and Polycarbonate. FDM produces durable, functional parts used for Prototyping applications and as Direct Digital Manufacturing for end-use parts.
SELECT	$639 Details	August 22	SLA	InterPRO	SLA offers good strength for verifying your designs, testing assembly fits and significant functional testing. Water clear models are available. InterPRO is ISO 9001-2000 compliant.
SELECT	$505 Details	August 25	ZCorp	Alchemy Models Inc.	Using Zcorp 510 printer and a new powdering system, parts enjoy 600 dpi, enhanced surface finish, great accuracy, fine details. Overall quality rivals SLA process. Only provider offering full-color.
SELECT	$607 - $641 Details	August 25	SLA	Vista Technologies	Well equipped with large platform machines and a Viper machine with a high resolution laser for small parts with tight tolerances. Vista offers multiple SLA resins from clear, flexible, and ABS-like.
SELECT	$750 - $1,000 Details	August 25	PJET	Vista Technologies	
SELECT	MANUAL QUOTE Details		PJET	InterPRO	PolyJet offers superior detail, with build layers of 0.0006". Material properties of PolyJet models are very similar to SLA. InterPRO is ISO 9001-2000 compliant.
SELECT	$785 Details	December 31	PJET	RedEye RPM	Build LARGE PolyJet prototypes, 19.7x15.7x7.9 inches. PolyJet materials provide superior feature detail and ultra-smooth surface finish with build layers of 0.0006 inch!

Figure 24. Example Quotes for a 5U P-POD at 1/2 Scale

The author decided to find out if there were companies who were willing to lease 3D printers on month-to-month basis. The first option was to use the ZCorporation printers since they had the cheapest online quotes. Unfortunately, there were no companies locally who leased ZCorporation printers. After contacting the local distributor for Dimension 3D printers, The Paton Group located in Los Angeles, it was found that they were willing to lease a Dimension printer for $1,000 per month. The cost of the material to build parts was $250 per 56 cubic inch cartridge, which is equivalent to $4.46 per cubic inch. A half scale 5U P-POD would use 9.78 cubic inches of model material and 7.89 cubic inches of support material. Both model and support were the same price, so the material cost of a 5U P-POD would be approximately $79 (17.67 cubic inches of material x $4.46 per cubic inch).

At a price of $79 per model and a two-month lease, it was clear that the option to lease a 3D printer would be considerably cheaper than hiring a RP company. Additionally by reducing the material cost of producing P-POD models, 3U and 6U models could also be built and it afforded some flexibility for some iterative design, in the engineering world commonly known as “mistakes”.

4. CAD Modeling

By far, the most time spent on this project was learning to use a CAD program and building, refining, and modifying the CAD files that would eventually be used to build the P-POD models. In addition to learning the basics of any CAD program, there are often many ways to accomplish any given task. There are probably a dozen major, well known CAD programs world-wide. Before this project, the author had some minor experience with both AutoCAD and Rhino3D. AutoCAD is far more popular in the United States, while Rhino3D is more popular in Europe. Almost all are capable of opening, and working with each other's CAD file types, although sometimes with a little difficulty. Most 3D printers require a stereo lithography (STL) output file. Every major CAD program is capable of producing files in STL format. STL files are at least an order of magnitude larger than the standard CAD files used by respective CAD programs. Working with STL files directly was far more taxing on the computer's resources and even caused software crashes on more than one occasion. The author determined that it was better to work with CAD models using the native file format of the CAD program, and then export the file to STL only for the purpose of sending the part to the printer.

STL files are simple files that take a 3D CAD model and divide it into a series of thousands or even millions of intersecting tetrahedral [10]. In many ways STL files are to 3D CAD models what "bitmap" files are to 2D digital photographs. They are simple, non-compressed, large files. Although the STL format is the same in both cases, the STL file can be saved using either ASCII or binary characters. The binary STL files were generally 25% as large as their ASCII counterparts. Interestingly there is no difference in detail between the ASCII and binary STL files despite the four fold difference in file size, so the author recommends saving binary type STL files if the printer driver is capable of accepting them.

STL files do not include the measurement units of the original CAD file, so one needs to tell the printer what the proper units of measurement are for the file. To guarantee the file resolution was adequate for the printer, the author exported files that were twice the maximum resolution of the printer. Since the author's CAD files were always built in inches, and the best printer resolution was 10 mils (.01 inches), all CAD parts were exported to STL files with .005 resolution when working with inches—twice the maximum resolution of the printer. The author exported some of the STL files to higher resolution (.0001—20x higher than normal) to conduct a side-by-side comparison of some of the finished parts he was building. As expected, there is no noticeable difference, even on the smallest most delicate parts, as long as the resolution of the output STL file is higher than that of the printer resolution (see Figure 25).

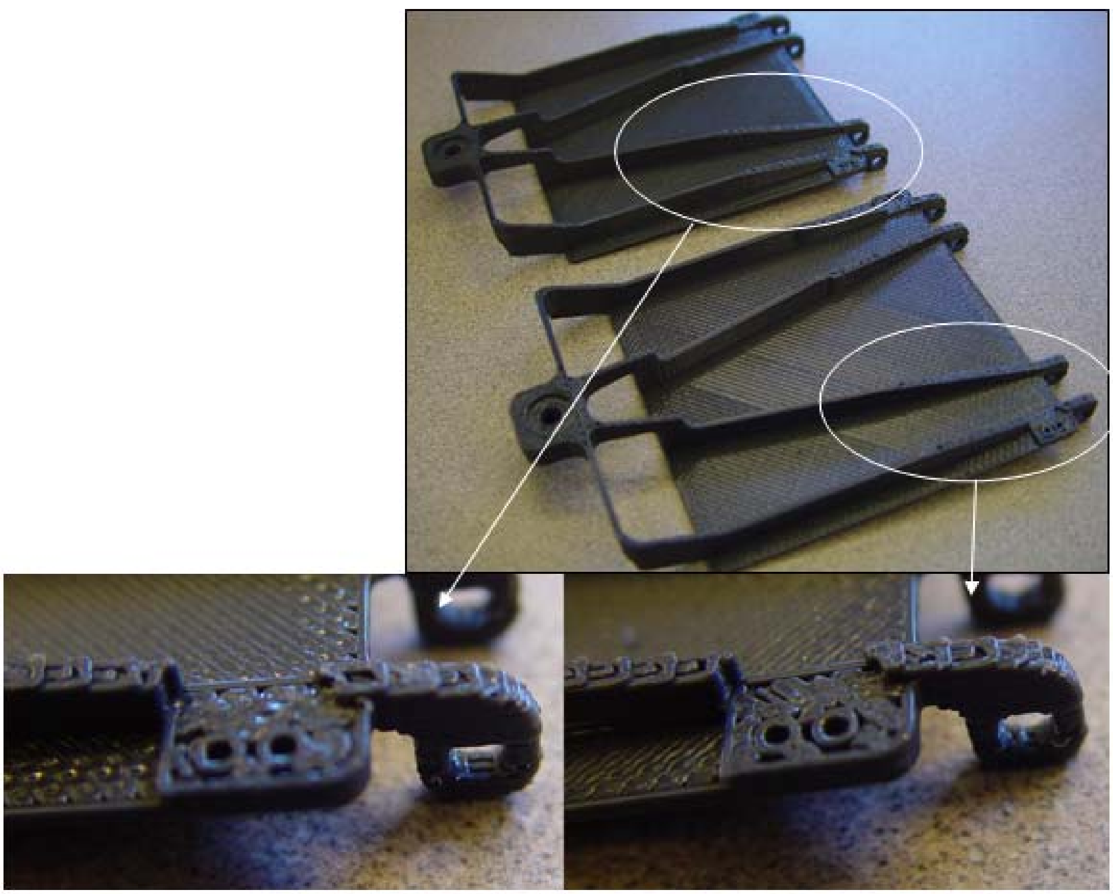

Figure 25. The model (bottom left) was built using .005 STL file resolution, while the model (bottom right) was built using .0001 STL file resolution.

5. 3D Printers

3D printers build 3D models or parts from a CAD file by layering and connecting cross-sectional areas one layer at a time. The printer software driver begins with the complete CAD model to be built. The driver then virtually divides the CAD model by slicing it into 2-dimensional layers that can be built, one at a time, on top of the previous layer. The thickness of each 2D layer depends on the resolution of the printer, typically between 5–13 mils.

The printer will then build the part using both the model material and support material, which supports the model during construction, but which will be removed later. When speaking or writing about 3D printers, the word “model” can become confusing since it can refer to a CAD “model”, the material used to build the finished part, or the finished part. For this document “model” only refers to the model material used by the 3D printer to build the finished product, but never the finished product itself or the CAD file.

Model and support are generally in a solid form before fabrication into a part in the 3D printer. Some printers have spools of model and support structure that are fed into the printer where they are heated and melted just before entering the print head. Other 3D printers use the same process except the model and support material are in a powder form before being melted. Whether the model and support are in powder form or on a spool, the rest of the fabrication process is more or less the same for all 3DP machines.

Model and support will be laid down by their respective print heads layer by layer. First support, then model for the first layer, then support then model for the second layer and so forth as depicted in Figure 26 below. Support structure literally supports the model in various ways. For parts of the model that overhang free space, the printer must build support structure first on which it can build the overhanging part. The support will be built up until the printer reaches the layer where the overhanging part begins, at which point it has built a foundation on which it can build that part.

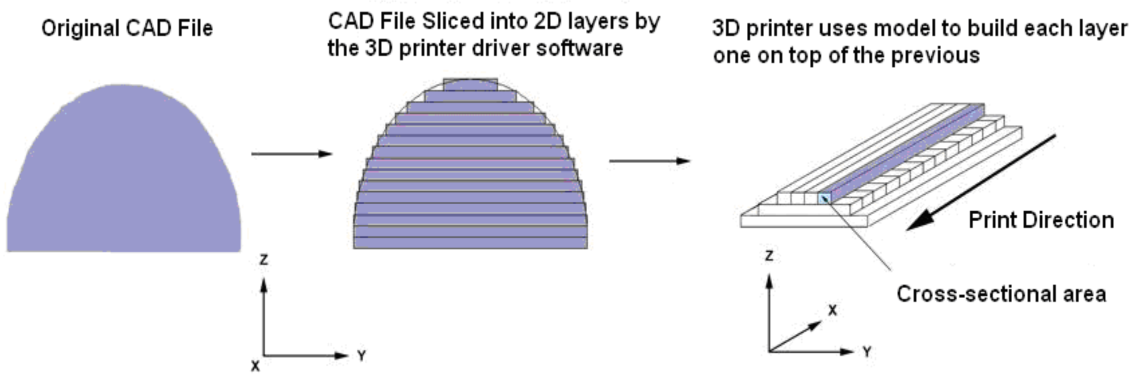

Figure 26. From a CAD Model to a 3D Object modified from [17]

The Paton Group in Los Angeles is the Dimension 3D Printer distributor for the state of California, and they were the only business the author was able to locate near NPS willing to lease 3D printers. Dimension offers 6 printer models ranging from $18,000–$35,000 each with various features. The most basic Dimension printers have a small build area, 8” x 8” x 10”, with 13 mil resolution, and build using ABS plastic. The more expensive models have a larger print area, 10” x 10” x 12”, slightly better resolution, 7 mils or 10 mils, and use “ABSplus” plastic, which is 40% stronger than standard ABS plastic. The ABSplus material also has a glossier finish, which is more aesthetically pleasing.

The inexpensive printers also use a “breakaway” support technology that allows the user to simply break away support from the model after removing it from the printer. Although breakaway technology is quick and easy to use, it poses problems for small, delicate parts since they can be broken while breaking the support away. The other option for support technology is soluble support, which can be dissolved away by placing the model in a sodium hydroxide ($NaOH$) solution commonly referred to as “lye,” which is heated in a bath to 70ºC. Most models take between one to four hours to dissolve the support material. Unfortunately, in this price range, breakaway support and soluble support are typically not interchangeable by machine; each machine can be used with only one type of support material. The author was given a choice between the Dimension 1200es and the Dimension Elite Printer (see Figure 27). These were

Dimension's two newest and most expensive printers at $34,900 and $32,900 respectively. Both printers featured the soluble support technology and used the ABSplus plastic. The Elite printer had the highest resolution of any Dimension printer selectable to 7 or 10 mils by manually changing print head, but the build volume was roughly ½ the size of the 1200es like the less expensive printers (8" x 8" x 10" or 640 cubic inches).

Figure 27. Dimension Elite (Left) and 1200es (Right)

At the higher 7 mil resolution, finished parts take approximately twice as long to build than at 10 mil resolution. The 1200es machine, on the other hand, had a larger print area (10" x 10" x 12" or 1200 cubic inches), but the resolution was lower, selectable to 10 or 13 mils. At 10 mil resolution, parts take approximately 70% longer to build than at 13 mil resolution, but only half as long as 7 mil resolution. In the end, the choice was between the Elite with 30% higher resolution, but at a sacrifice of print time, and only half the maximum print

volume, or the 1200es with 30% lower resolution at the reward of twice the speed and print volume. Despite the lower resolution, considering that many large parts were needed, the author chose the Dimension 1200es.

6. Building Parts on the 3D Printer—Lessons Learned

The orientation in which the part is built affects the amount of support material the printer will need to finish the part, the amount of time needed, the surface finish, and strength of the part. The printer can build each layer in any order or direction it chooses, giving freedom in the x and y direction. However, it must complete the layer before moving on to the next layer above. Therefore, while it can build the model such that it optimized the x and y directions for strength, the z-direction must be built sequentially from bottom up. Notice in Figure 26. , the printer built the first layer (on the bottom) by laying down lines of model along the x-direction. The next successive layer was laid down with each line along the y direction, and so on to the next layer. The weakest part of any given layer is between each successive line of model. If the printer were to lay down each line along the same axis, rather than alternating each successive layer, then the group of layers would be weak perpendicular to the print direction and very strong along parallel to the print direction. By alternating the direction in which each layer is printed makes the object strong in both the x and y directions.

When it comes to the z-direction, on the other hand, the printer has no ability to alternate the layers with either of the other two directions causing the z-print axis for any given object to always be weaker with respect to force applied perpendicular to the z-axis.

The surface finish is affected by the orientation in which the printer builds the object. The printer is not only capable of free movement exactly parallel with either the x or y axis, but it can move in any direction or angle within each plane. This is important, especially when building some parts expected to move and interact together such as hinges. When a hinge is built so that its length is parallel to the z-axis (up and down), the printer can print each layer of the hinge

in circular rings, one on top of the next. Each subsequent layer gives the finished hinge a smooth surface finish, necessary for the hinge to operate smoothly. A hinge built perpendicular to the z-axis, on the other hand, will naturally have a rough finish since it would be necessary to stare-step layers approximating the circular part of the hinge. Notice the smooth finish on the hinge displayed in Figure 28. If the part had been built such that the hinge length was parallel to the x-y plane it would have been stair-stepped and had a rough finish that would not operate smoothly with the other half of the hinge.

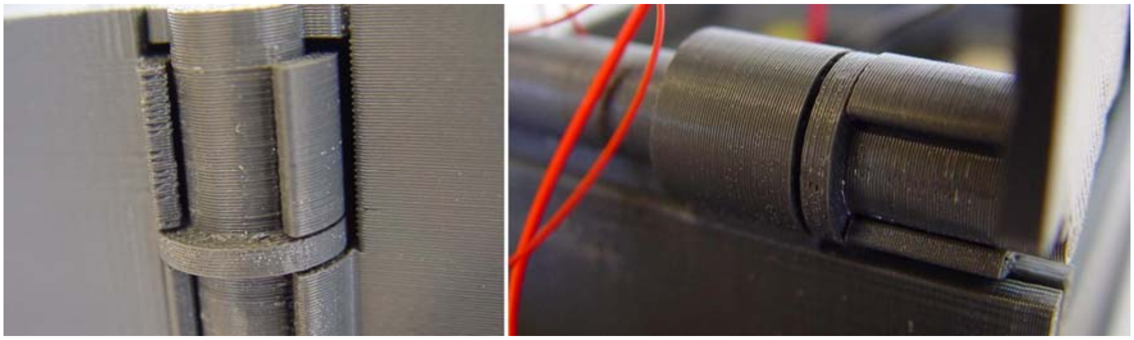

Figure 28. Two Views of the same 3D Printed Hinge

The amount of support material needed varied depending on the orientation used to build a part. For any given CAD model, depending on the orientation, there may be parts that will overhang free space. Clearly the printer cannot print with model suspended in free space, so the printer must first build a support structure underneath anything that would otherwise be hanging freely. A great example is an open box. If the box is built with the base down and top open, very little support material will be needed. If that same box were to be built upside down, such that the base of the box would be located at the top, this would require the machine to build support structure inside the box as it is building the sides, so when it eventually reaches to top, it has something on which to build the base of the box. This orientation would use significantly more support than if the base of the box were located on the bottom.

The build time could also be affected by the object orientation. Between each layer the printer will return to the home position and purge the print head once after the support is laid down, then again after the model is laid down. If something, such as a P-POD, which is fairly long and skinny, were built so that the long direction is in the z-direction, there would be many more layers than if it were built in another direction. Since there are approximately 100 layers per inch (at 10 mil resolution), for every inch tall an object is, the printer must return to home and purge the print head 200 times (twice per layer – once for material and support each). In general, it requires the printer less time to build objects when the long direction is any direction other than the z-direction.

Sometimes build time and support material can both be saved by splitting the CAD file into more basic parts and performing some minor manual construction later. Whether the material savings and time savings on the printer are worth the extra time spent afterwards assembling the final product varies on a case-by-case basis. On the 3U P-POD below, the side panes looked considerably better when built in the horizontal direction.

Table 3. below compares the print time, and support material required to print a 5U P-POD with the long edge vertical, horizontal, and horizontal and the side panel removed. The print time was assumed to be worth approximately $2.00 per hour based on $1,000 per month lease at a printer utilization rate of 70% of the time (500 hours out of 720 hours per 30 day month). Model and support are $4.46 per cubic inch.

Vertical printing uses less support material than horizontal printing in this case for a material savings of almost $5.00, but costs an additional 3 ½ hours of print time. If concerned only with minimizing printer costs, then one can further reduce the cost by removing the side panel while in the horizontal orientation, which results in the object being built using the least amount of support and time. For the 5U P-POD, this is a savings of about $20 per finished product, and would cost about 5 minutes to re-attach the side panel using glue after the printer was finished.

5U P-POD Statistics at 10 mil resolution.						
	Material	Support (cubic inches)	Time (hours)	Total cost of material	Total cost of time	Total
Vertical	9.73	9.74	22:43	$86.91	$45.43	$132.35
Horizontal	9.76	11.02	18:22	$92.76	$36.73	$129.50
Horizontal with side panel removed	9.78	7.89	15:21	$78.88	$30.70	$109.58

Table 3. 3U P-POD Print Statistics at 10 mil resolution

Most of the 5U and 3U P-PODs were printed horizontally with the side panel removed, which saved the project $200–$250 worth in material costs, but it may not have been worth the effort. For the 3U P-PODs it was not significant, but for the 5U P-PODs, it was. Since the 5U P-POD at half scale is too long to print in a single piece the P-POD was split into a top and bottom half, additionally the side panel was removed from both halves for a total of four pieces. After final assembly, the author noticed that the top and bottom section did not fit together as tightly as possible leaving an un-slightly gap between the top and bottom sections. This gap is caused because it was nearly impossible to reattach the side panel perfectly, causing a slight mismatch in the z direction between panel and the rest of the P-POD to which it was attached. This slight difference, probably less than a millimeter, caused the bottom and top sections of most 5U P-PODs to not fit exactly when assembled into a single piece.

The lesson learned from this experience is to avoid dividing objects to be built by a 3D printer into multiple pieces beyond what is absolutely necessary due to the printer volume constraints. The idea that objects can be easily re-assembled afterwards may not always be true. In reality, reassembly can be much more difficult than originally anticipated.

7. NPSCuL Functional Prototype – the Finished Product

The Functional Prototype was finished at the beginning of August 2008. The main structure was made of Aluminum 5056 and coated with an anodyne finish giving it a gold color. The P-PODs were built with the 3D printer using gray

ABSplus plastic, similar to the color of real flight-ready P-PODs. P-PODs were built in 3U, 5U and 6U varieties and were attached with Velcro to the NPSCuL. The Velcro is convenient since it allows the team to easily demonstrate the versatility of NPSCuL by reconfiguring the various types of P-PODs that can be loaded onto the NPSCuL slots.

To add more realism to the final product springs were added to the P-POD doors to allow them to spring open much like actual P-PODs. To hold the door shut a small plastic arm is attached to the servo, which allows the door to spring open on command (see Figure 29). One of the team members took this a step further and built a sequencer from a BASIC Stamp controller, which could control up to eight servos at a time. Using this controller, which was named “CubeCon” (short for Cube Control), a single push of a button could simulate the deployment command from a launch vehicle and cause eight of the attached P-PODs to spring open sequentially with a small time delay between each. In the future a spring may be added to the inside-bottom of each P-POD to allow something to spring out as each P-POD opens. Figure 20 below shows the CubeCon box both closed and open to expose the circuitry inside.

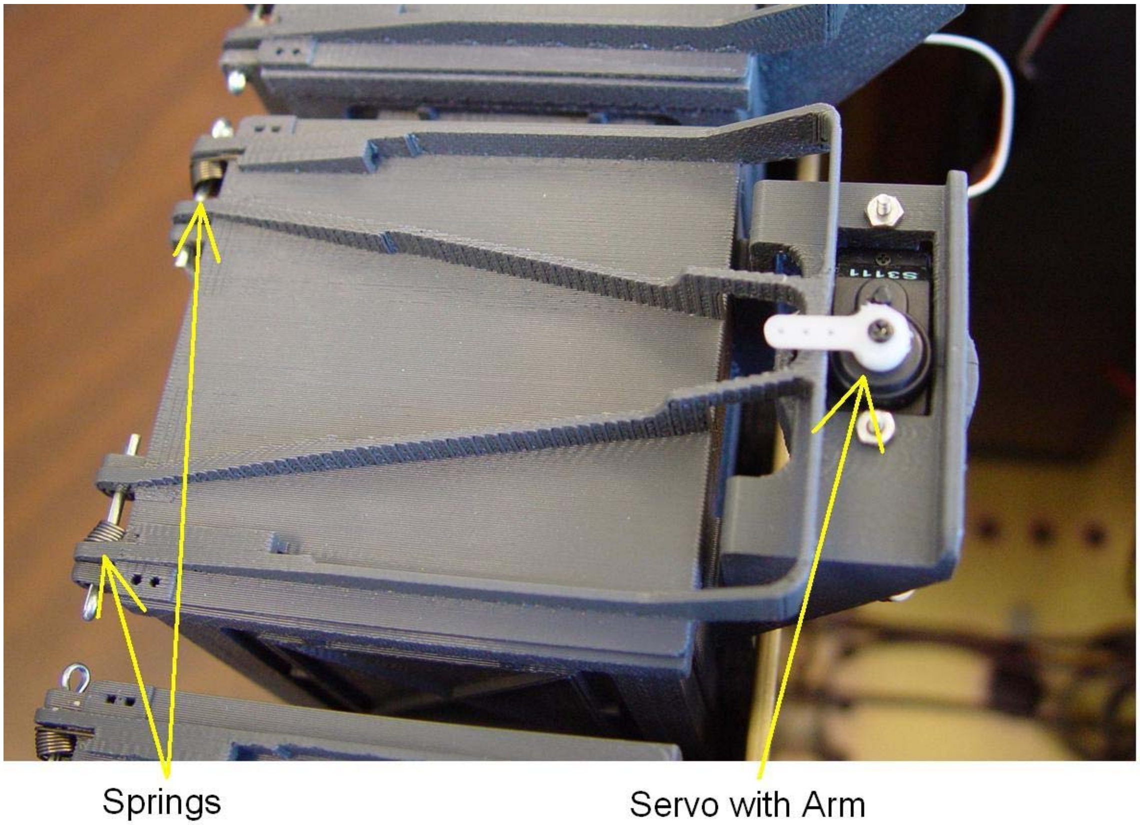

Figure 29. P-POD Springs and Servo

The CubeCon box additionally demonstrates the benefit of RP technology. The directed study student who built the sequencer needed a protective box to hold the stamp circuitry and associated hardware such as the battery, connectors, push buttons, LED lights, etc. Rather than build a simple box, with some help from the author, he built a CAD model complete with hinges and clasps, not only to hold the circuitry and other hardware, but also allow it to be easily accessible by opening the box. Notice inFigure 30, when the box is closed everything is protected, but when the box is opened, the circuitry is exposed, including both sides of the BASIC Stamp controller board in the center. In fact the first iteration of the CubeCon box did not work—among other things, the clasp broke the first time it was used, the hinge was too rough and tolerances for the hinge were too tight, the box was flimsy so the corners of the box didn't line up when closing the box. After the first CubeCon box was built the author was

able to fix the problems on the CAD model in less than an hour, and began printing a new iteration. The second iteration has not experienced any of the problems of the original; this is an example of how the iterative nature of engineering can benefit from RP technologies' rapid turn around time.

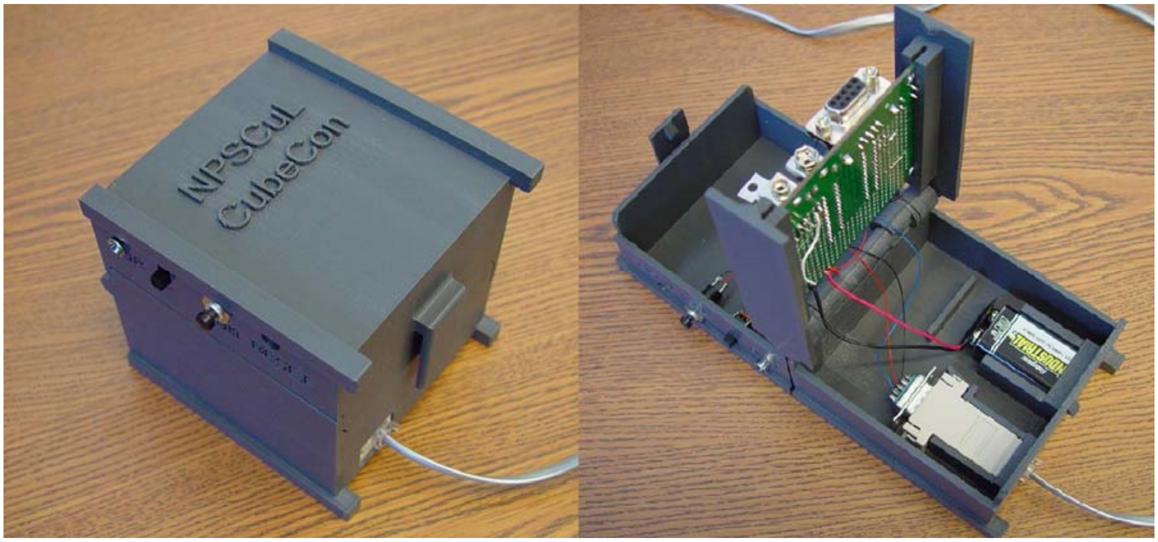

Figure 30.   NPSCuL CubeCon. Closed (left) and Open (right)

The final NPSCuL functional simulator debuted at the 2008 Summer CubeSat workshop, preceding the Small Satellite Conference in Logan, UT in August 2008. The author made a twenty-minute presentation that was well received by the audience as evidenced by the number of questions after the presentation finished. It became clear that functional hardware is much more effective at demonstrating an engineering concept, such as NPSCuL, then pictures and words alone. The NPSCuL functional mass simulator will without a doubt prove useful in the future as it is presented to the CubeSat community.

The final figures in the section are of the NPSCuL ½ scales model (Figure 31) along with several of the other models built as part of this project. (Figure 32).

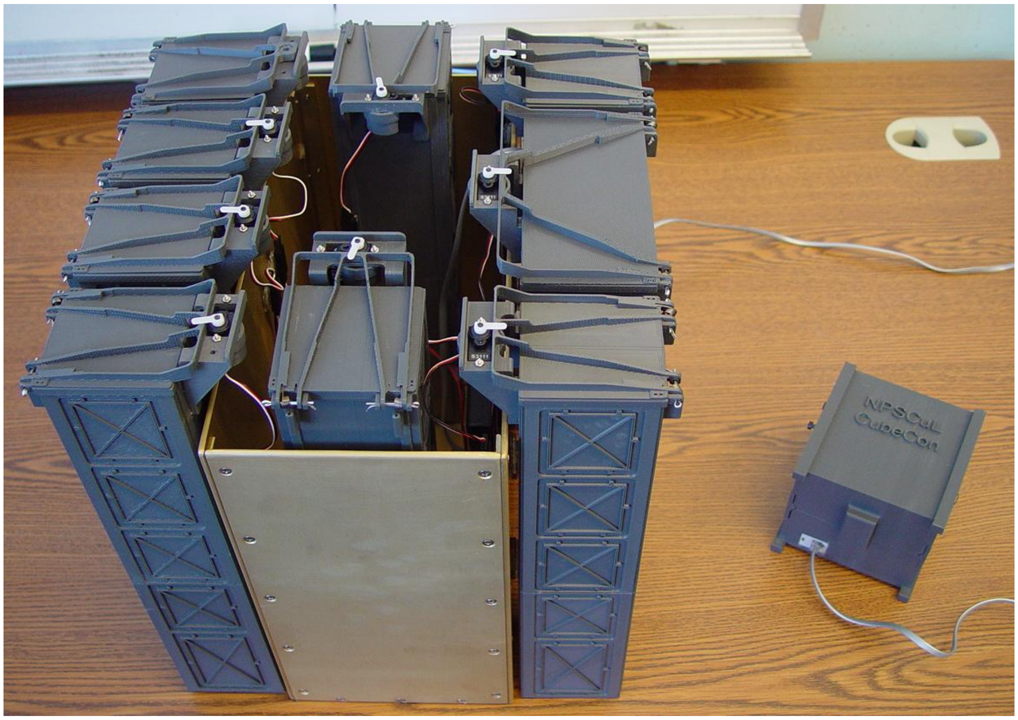

Figure 31. NPSCuL ½ Scale Functional Model

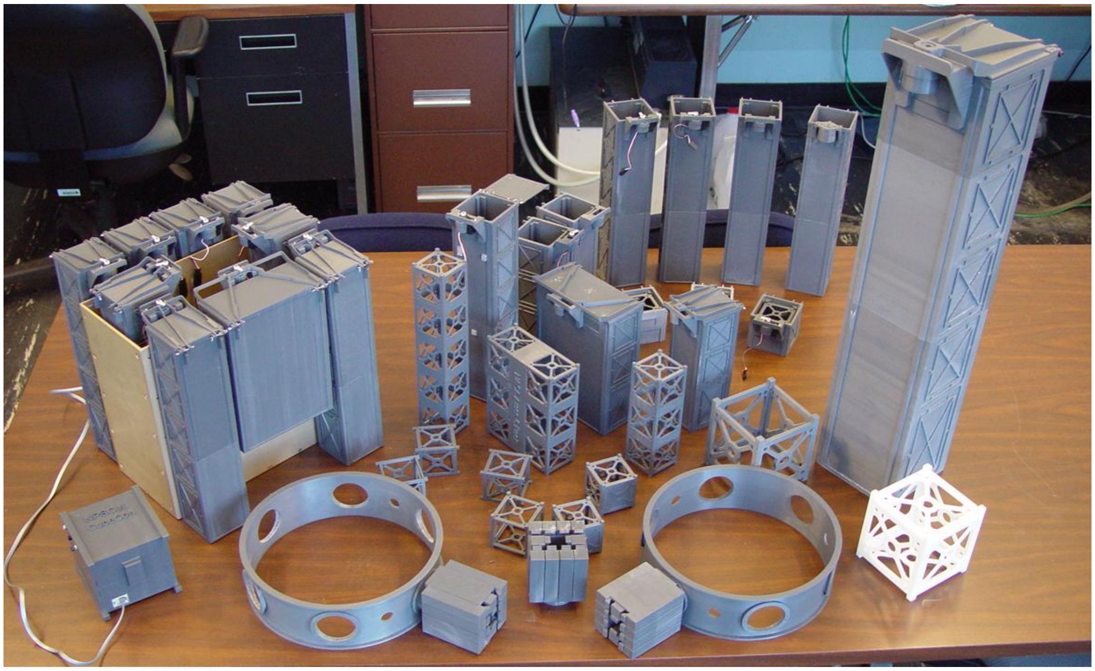

Figure 32. Parts made for the NPSCuL Project with the 3D Printer

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IV. NPSCUL PROGRAM MANAGER

A. PROGRAM MANAGER DUTIES

The NPSCuL project was unique because unlike most student theses where the student may be in charge of a project, but funding and schedule are generally managed by the thesis advisor, the author acted as the Program Manager for the NPSCuL project. As the Program Manager, the author felt a strong sense of ownership and responsibility for the project. Some of the responsibilities that he had as Program Manager that one might not have had otherwise were to:

1. Manage the Budget.
2. Manage the Schedule.
3. Recruit new students to take over the project before he left.
4. Authority to make important decisions for the project.
5. Responsibility for all deliverables due to CSEWI and quarterly reports.

B. BUDGET

Part of the responsibilities as Program Manager, were to manage the budget. The grant money was provided by the Department of Labor's WIRED initiative through the CSEWI. CSEWI recognized the potential of NPSCuL, and realizes that by funding development of an NPSCuL, it may facilitate domestic CubeSat research and launch for California-based institutions such as Stanford, California Polytechnic State University, Boeing and others. CSEWI provided a grant for $20,000 for NPSCuL using a CRADA with NPS. The Naval Postgraduate School collects 31.59% of the costs as "indirect costs". Indirect costs are used to pay for lab space, utilities, administrative support, and other associated costs relating to hosting a research project.

The amount of money used to build the hardware mock-up was difficult to estimate in the beginning since it varied greatly depending on the method used. In the end, the hardware mock-up cost a total of $6,178.52, travel was $7,783.93, and indirect costs were $4,801.27. At the time of this publishing, there was $1236.28 remaining in the budget, which has until the end of January 2009 to be spent by the new program manager.

Since this project was conceptually straight forward, the author used a Microsoft Excel spreadsheet to manage the budget. The budget spreadsheet can be found in Appendix C. In the authors opinion the biggest lesson learned was the difficulty of accurately estimating costs. Even on a small project such as this one, costs estimates may be off by as much as a factor of two. Originally, $4,500 was budgeted for travel and $11,000 for construction of the prototype. The prototype cost a mere 56% of the original estimate, while travel cost almost 94% more. Originally, the author considered travel optional. Due to some savings by renting a 3D printer, for example, more students were able to attend conferences relevant to the project. This taught me the value of having some small budget margin, which can allow for some flexibility in a project for which it can be difficult to accurately forecast costs.

Attending conferences provided an important lesson in the value of face-to-face communication early in a new project. The DoD Rideshare conference was hosted by the NASA Wallops Flight Facility, in Wallops, Virginia. Originally, the author thought it was optional and had the budget not supported attending it would have been cut from the schedule. While at the conference however it was realized how well the NPSCuL project would fit with the overall theme of the conference. Those in charge of the conference were able to fit a short NPSCuL presentation into the conference on the last day, which was made by the author. Immediately after the presentation, the author and other NPS attendees were approached by a party from the U.S. government who was interested in funding the development of NPSCuL. The team submitted a proposal to this

organization, which have now begun funding NPSCuL for the 2009 fiscal year. Clearly this opportunity may have been missed if the conference had been skipped.

C. SCHEDULE

The author used Microsoft Project to manage the schedule. The schedule spanned the timeframe from January 2008 through September 2008, which was the time the author expected to be working on the project. The majority of the project was dedicated to all aspects of building the demonstration prototype, since this required the most time of anything else in this thesis. To summarize the schedule, the month of March was spent investigating various forms of rapid prototyping, cost estimating the various options, and eventually arranging for the lease of a printer. The remainder of the time was spent preparing 3D CAD models before the printer arrived. The CAD models took a particularly large amount of time, since the student was also simultaneously learning to use the CAD program and experienced difficulty with the P-POD files obtained from Cal Poly. The printer was acquired on April 5. Over the subsequent three months, the student spent many hours building 3D CAD files, and printing them on the printer. He found that having a 3D printer at hand was invaluable, since it allowed him to re-work a CAD file immediately when he found a problem or mistake with a printed 3D object. Had the team contracted with an online 3DP company, mistakes would have been far more costly and would have had slower turn-around time, unnecessarily delaying the project. Appendix D is a printout of the MS Project schedule used for this project.

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V. CONCLUSION

A. FUTURE OF NPSCUL

Given the success of the NPSCuL program over the past year, and the partial funding received, the SSAG has decided to begin development and testing on the qualification unit in FY09. The timeline is still fluid since it depends partially on funding received from various government groups. One government agency is currently interested in the NPSCuL-Lite and has begun funding it for development over the next eleven months, beginning October 2008.

Before a flight ready NPSCuL or NPSCuL-Lite can be completed there are several tasks, which would require completion. The following is a basic summary of the tasks necessary to build a flight ready NPSCuL. While, the speed with which steps below can be completed is somewhat dependent on the funding available, although the funding may more directly affect the fidelity of testing and amount of risk with which the project can be completed. With more funding, to increase testing fidelity, the testing can be performed with real P-PODs. With additional funds it might be possible to hire external testing facilities as necessary if NPS facilities were unavailable or inadequate, which would reduce the overall program risk.

Although the steps are in sequential order, many tasks can commence and be performed in parallel with other tasks on the list.

1. Finish and conduct finite element analysis on the final design.
2. Construct a prototype NPSCuL unit
3. Finish the design for a flight ready sequencer
4. Construct a prototype sequencer for testing
5. Conduct preliminary vibration, shock and thermal testing on the prototype NPSCuL and sequencer. For these tests build and use mass models for P-PODs

6. Make any necessary changes to the designs based on findings from the prototype.
7. Build a qualification unit.
8. Conduct qualification level vibration, shock, thermal and (for the sequencer) EMI testing. For high fidelity tests use real P-PODs in the locations they will endure the most extreme launch environment and P-POD mass simulators elsewhere.
9. Build the Flight unit.
10. Conduct acceptance testing on the flight unit.
11. Build a harness for lifting a fully integrated NPSCuL.
12. Build a transport container for shipping NPSCuL to the launch integration site.

In addition to the above steps there is much research that could be completed relating to NPSCuL, but not necessarily required for production of a flight NPSCuL. Some ideas are included the below.

1. Conduct an in-depth analysis of the collision possibility for such a high number of CubeSats. Although the probability of collision is anticipated to be very low or zero, an analysis may put would-be critics' minds at ease. Although the author appreciates the importance of orbital debris mitigation, in his opinion, many with a limited understanding of orbital mechanics tend to dramatically over-estimate the risk associated specifically with CubeSats and on-orbit collision probability. CubeSats tend to have a low orbit yielding a short orbital lifetime of months to two years before re-entering earth's atmosphere, so the effect on LEO debris should be both short-term and minimal. This might also be useful to determine if there is a lower collision possibility by releasing CubeSats before, after, or at the same time as other small secondary payloads.

2. Conduct mass optimization analysis of NPSCuL and NPSCuL-Lite. It may be possible to accommodate 5U P-PODs on a future NPSCuL-Lite iteration since mass is the limiting factor on the ABC for accommodating more CubeSats. This design might be able to accommodate up to 40U when attached to the ABC, and possibly even more when attached to the ESPA. If such a design existed it could fulfill the purposes of NPSCuL-Standard and NPSCuL-Lite with a single design.

3. Conduct a study to determine if additional requirements should be necessary for CubeSats flying on NPSCuL. For instance, should radio frequency Identification (RFID) beacons be required for all CubeSats? (It may be very difficult to locate a specific CubeSat with so many being deployed at one time.)

The CubeSat community is still in its infancy and there may be several other areas of study that should be addressed regarding NPSCuL not covered here.

B. CLOSING REMARKS

Considering the growth of the CubeSat community it seems clear that CubeSats may have the potential to revolutionize the way experiments are performed on orbit. The CubeSat, although based on a 1U building block, is scalable and the community is now starting to see larger CubeSats. As the CubeSat community grows, and COTS parts for CubeSats increase in variety and performance, much like other technologies the have emerged, and then matured over time (such as computers, the internet, cell phones, etc) the use of CubeSats may develop in ways not currently imagined.

NPSCuL has the potential to become the first high capacity CubeSat deployment mechanism. High capacity launch is essential if the CubeSat community is to continue the growth experienced in the past six years.

Additionally if the U.S. expects to be in the lead in this new innovative technology, it must not only build, but launch CubeSats.

The NPSCuL concepts have a simple design, which not only reduces development and reproduction costs, but reduces risk of failure. NPSCuL or NPSCuL-Lite are a reasonable first step to domestic, high-capacity CubeSat launch that, with proper funding, could be built within a year. NPSCuL should be developed as a way to reduce the cost of deploying CubeSat experiments in space and enabling domestic CubeSat developers to innovate in technology and education.

LIST OF REFERENCES

[1] California Polytechnic State University, CubeSat Design Specification. 15 May 2005, last accessed June 2009.Cubesat.atl.calpoly.edu/media/Documents/Developers/CDS%20R9.pdf.

[2] Isaac Nason, Jordi Puig-Suari, Development of a Family of Picosatellite Deployers Based on the CubeSat Standard, last accessed September, 2008. http://ssdl.stanford.edu/ssdl/images/stories/papers/2002/ssdl0206.pdf.

[3] California Polytechnic State University, P-POD Mk III ICD. 23 July 2008, last accessed June 2009. cubesat.atl.calpoly.edu/media/P-POD%20Mk%20III%20ICD.pdf.

[4] Worden, Pete S. The Scientific Promise of Small Satellites 28 June 2007, last accessed 29 September 2008. http://www7.nationalacademies.org/ssb/ssb_june07_scientificpromisesmallsatellites.pdf.

[5] Leonard, David, CubeSats: Tiny Spacecraft, Huge Payoffs, 8 September 2004, last accessed 25 September 2008. http://www.space.com/businesstechnology/cube_sats_040908.html.

[6] Brooks, Lori, CubeSat Developers Workshop April 2007, last accessed 28 September 2008. http://atl.calpoly.edu/~bklofas/Presentations/SummerWorkshop2007/Brooks_Lori.pdf.

[7] Cowing, Keith, SpaceX Determines Cause of Falcon 1 Failure, 6 August 2008,last accessed 25 September 2008. http://www.spaceref.com/news/viewnews.html?id=1302.

[8] Reported by California Polytechnic State University at the CubeSat Workshop, August 2008 at Utah State University in Logan, Utah.

[9] DoD Space Test Program, Secondary Payload Planner’s Guide For Use On The EELV Secondary Payload Adapter, Version 1.0, 8 June 2001 last accessed June 2009. http://web.ew.usna.edu/~midstar/downloads/structures/ESPA_Payload_Planners_Guide.pdf.

[10] RP Technologies Website, last accessed on 25 September 2008. http://www.rapidprototypinghomepage.com/#COM.

[11] Standard Navy Cooperative Research and Development Agreement between Naval Postgraduate School and California Space Education & Workforce Institute, Student Rideshare Payload Model, Agreement Number NCRADA-NPS-08-0104.

[12] NPS PANSAT Website, last accessed 25 September 2008. http://sp.nps.edu/pansat/.

[13] NPS NPSAT1 Website, last accessed 25 September 2008. http://sp.nps.edu/npsat1/.

[14] J.H. Newman, D. Sakoda, and R. Panholzer, "CubeSat Launchers, ESPA-rings, and Education at the Naval Postgraduate School", *21st Annual AIAA/USU Conference on Small Satellites*, Logan, UT, August 2007.

[15] Roßberg, Felix, Structural Design of a NPS CubeSat Launcher, January 2008. Naval Postgraduate School, Monterey CA.

[16] Planetary Systems Corporation, "2000785 Rev – User's Manual for Mark II Lightband", September, 2007, last accessed September 2008. http://www.planetarysystemscorp.com/download/2000785A_UserManual.pdf.

[17] The Wikipedia Project, "Rapid Prototyping," last accessed 26 May 2009. http://en.wikipedia.org/wiki/Rapid_prototyping.

APPENDIX A. LIST OF CUBESAT DEVELOPERS

US Universities					
State		Universtiy	Website, Contact Person and Email (if available)		
Alabama	1	Auburn University	http://space.auburn.edu/	Luther Richardson	lrich@physics.auburn.edu
	2	University of Alabama, Huntsville	http://www.seds.org/archive/sedsat/		maier@ece.uah.edu
	3	Tuskegee University		Vascar Harris	
Arizona	4	Arizona State University	http://nasa.asu.edu/asusat	Helen Reed	Helen.Reed@asu.edu
	5	University of Arizona	http://uasat.arizona.edu	Mike Drake	drake@lpl.arizona.edu
California	6	Cal Poly State University	http://polysat.calpoly.edu/	Jordi Puig-Suari	jpuigsua@calpoly.edu
	7	Cuesta College	http://www.cubesat.com/links.htm		
	8	Naval Postgraduate School		Jim Newman	jhnewman@nps.edu
	9	San Jose Sate University		Dick Desautel	dick.desautel@sjsu.edu
	10	Stanford University	http://ssdl.stanford.edu/opal/home.html	Bob Twiggs	bob.twiggs@stanford.edu
	11	University of California Irvine		Divya Patel	
	12	University of California Santa Barbara	www.conolley.com/cubesat/	Marko Peljhan	
Illinois	13	University of Chicago		Geza Gyuk	ggyuk@adlerplanetarium.org
	14	University of Illinois - at Urbana-Champaign	http://cubesat.ece.uiuc.edu/	Gary Swenson	swenson1@uiuc.edu
Colorado	15	University of Colorado - Boulder	http://spacegrant.colorado.edu/	Chris Koehler	Koehler@colorado.edu
Florida	16	Florida Institute of Technology		Michael Letsky	
	17	Embry-Riddle Aeronautical University		Ary Glantz	aryjglantz@hotmail.com
	18	University of Central Florida			
	19	University of Florida - Gainsville			
Hawaii	20	University of Hawaii	www-ee.eng.hawaii.edu/~cubesat/	Wayne Shiroma	cubesat@spectra.eng.hawaii.edu
Indiana	21	Purdue University		David Filmer	filmer@ecn.purdue.edu
	22	Taylor University	www.css.tayloru.edu/~physics/picosat/	Hank Voss	hnvoss@tayloru.edu
	23	SUNY Geneseo		Josh Reiner	wersing@physics.auburn.edu
Iowa	24	Iowa State University		Thomas Calgaard	tmichael@iastate.edu
Kansas	25	University of Kansas		Trevor Sorensen	tsorensen@ku.edu
Lousiana	26	University of Louisiana		Robert Henry	henry@louisiana.edu
Maryland	27	US Naval Academy		Bob Bruninga	bruninga@usna.edu
	28	University of Maryland Eastern Shore (UMES)			

US Universities (Continued)

State		Universtiy	Website, Contact Person and Email (if available)		
Massachusetts	29	Boston University		Don Wroblewski	dew11@bu.edu
	30	Dartmouth College		Shaina Damm	
	31	Boston University			
Michigan	32	Michigan Technological University	www.aerospace.mtu.edu/aeroweb/	Brad King	lbking@mtu.edu
Missouri	33	Wasington University - St. Louis		Mike Swartwout	mas@mecf.wustl.edu
	34	Saint Louis University			
Montana	35	Montana State University	www.ssel.montana.edu/merope/	David Klumpar	merope@ssel.montana.edu
New Mexico	36	New Mexico State University		Stephen Horan	shoran@nmsu.edu
New York	37	Cornell University	www.mae.cornell.edu/cubesat/	Mark Campbell	mc288@cornell.edu
	38	Polytechnic University – NYC		Ximing Li	
	39	State University of New York at Geneseo			
North Carolina	40	North Carolina State University		Tommy Sebastian	tsebast@ncsu.edu
North Dakota	41	University of North Dakota	www.und.nodak.edu/org/zamboni/	William Semke	william_semke@mail.und.nodak.edu
Oklahoma	42	University of Oklahoma		Brandon DeKock	
Texas	43	University of Texas - Austin	http://gps.csr.utexas.edu/sdl/index.html	Cesar Ocampo	cesar.ocampo@mail.utexas.edu
	44	Texas Christian University		Andre Mazzoleni	A.Mazzoleni@tcu.edu
	45	Texas A&M		Diane Hurtado	d-hurtado@tamu.edu
Utah	46	Utah State University		Chad Fish	
Virginia	47	George Mason University		Eliud Bonilla	ebonilla@gmu.edu
Washington	48	University of Washington		Adam Bruckner	Bruckner@aa.washington.edu
Washington D.C.	49	George Washington University		Jer-Nan Juang	J.JUANG@LaRC.NASA.GOV

International Universities

Country		Universtiy	Website, Contact Person and Email (if available)		
Argentina	50	Universidad de Buenos Aires		Gustavo Fano	
Australia	51	University of Sydney	http://cassat.acfr.usyd.edu.au/	Salah Sukkarieh	salah@acfr.usyd.edu.au
Brazil	52	UNOPAR University		Fernando Stancato	
Canada	53	Carleton University	www.scs.carleton.ca/~barbeau/Picosat/	Michel Barbeau	barbeau@scs.carleton.ca

International Universities (Continued)

Country		Universtiy	Website, Contact Person and Email (if available)		
Canada	54	University of Sherbrooke		Jean deLafontaine	Jean.deLafontaine@USherbrooke.ca
	55	University of Toronto	www.utias-sfl.net/nanosatellites/CanXProgram.html	Robert Zee	rzee@utias-sfl.net
China	56	Tsinghua University		Li Luming	lilm@tsinghua.edu.cn
Colombia	57	La Universidad Sergio Arboleda, Bogota Colombia		Cesar Ocampo	cesar.ocampo@mail.utexas.edu
Denmark	58	Aalborg University, Denmark	http://aausatii.space.aau.dk/	Rafal Wisniewski	raf@control.auc.dk
	59	Technical University of Denmark	http://dtusat.dtu.dk/	Peter Meincke	pme@oersted.dtu.dk
Germany	60	Fachhochschule Aachen	www.raumfahrt.fh-aachen.de/	Artur Scholz	cubesat@fh-aachen.de
	61	Julius-Maximilians-Universitaet Wuerzburg		Klaus Schilling	schi@informatik.uni-wuerzburg.de
	62	Technical University of Berlin	www.beesat.de/	Dr. Hakan Kayal	Hakan.Kayal@TU-Berlin.de
	63	University of Applied Sciences - Weingarten	www.informatik.uni-wuerzburg.de/lehrstuehle/lehrstuhl_fuer_informatik_vii/projekte/cubesat/uwe-1/	Klaus Shilling	schi@ars.fh-weingarten.de
	64	University of Siegen, Germany		Dr. Hubert Roth	roth@rst.e-technik.uni-siegen.de
Hungry	65	Budapest University of Technology and Economics			
India	66	New Dehli		Deepak	daksh@vsnl.net
	67	Vellore Institute of Technology Universtiy			
Italy	68	University of Trieste, Italy		Anna Gregorio	gregorio@sci.area.trieste.it
	69	Universita di Roma, Italy		Fabio Santoni	fabio.santoni@uniroma1.it
Japan	70	Tokyo Institute of Technology, Japan	http://lss.mes.titech.ac.jp/	Saburo Matunaga	Matunaga.Saburo@mes.titech.ac.jp
	71	University of Tokyo, Japan		Shinichi Nakasuka	nakasuka@space.t.u-tokyo.ac.jp
	72	Nihon University,Japan	http://cubesat.aero.cst.nihon-u.ac.jp/english/software_e.html	Y. Miyazaki	miyazaki@forth.aero.cst.nihon-u.ac.jp
	73	Soka University, Japan		Seiji Kuroki	kuroki@ieee.org
Lebanon	74	Beirut Arab University			
Malaysia	75	University of Malaysia		Faizal Allaudin	taiko2k@hotmail.com

International Universities (Continued)

Country		Universtiy	Website, Contact Person and Email (if available)		
Netherlands	76	Delft University of Technology	http://www.delfic3.nl/	Robbert J. Hamann	R.J.Hamann@LR.TUDelft.NL
Norway	77	Narvik University College			
	78	Norwegian University of Science Technology		Egil Eide	eide@tele.ntnu.no
Pakistan	79	Institute of Space Technology			
Poland	80	Warshaw University of Technology		Andrzej Kotarski	andrzej.kotarski@gmail.com
Purtugal	81	Faculdade de Engenharia da Universidade do Porto		Pedro Portela	portela@fe.up.pt
	82	University of Porto		Tiago Oliveira	em00165@fe.up.pt
Romania	83	University of Bucharest		Mugurel Balan	mugurel.balan@gmail.com
Saudi Arabia	84	Beirut Arab University		Rabie Kalash	rkalash@hotmail.com
South Africa	85	University of Stellenbosch		Arno Barnard	abarnard@sun.ac.za
South Korea	86	Hankuk Aviation University		Young-Keun Chang	ykchang@mail.hangkong.ac.kr
Spain	87	La Salle University, Barcelona		Javier Lazaro	jarribas@salleurl.edu
	88	Miguel Hernandez University of Elche			
	89	University of Navarra			
Switzerland	90	Federal Technical University of Lausanne		Muriel Noca	muriel.noca@epfl.ch
	91	University of Applied Sciences of Southern Switzerland		Paolo Ceppi	paolo.ceppi@supsi.ch
Taiwan	92	National Cheng Kung University Taiwan		J.J.	jjmiau@mail.ncku.edu.tw
Turkey	93	Turkish Air Force Academy		Fuat Ince	fuat.ince@superonline.com
	94	Bahcesehir University		Cengiz Toklu	yct001@gmail.com
	95	Istanbul Technical University		Dr. A. Rüstem Aslan	aslanr@itu.edu.tr
Ukraine	96	Institute of Technical Mechanics, Ukraine, Dnepropetrovsk		Anatoly Alpatov	alpatov@ukr.net
United Kingdom	97	Imperial College		Dr. Tim Horbury	t.horbury@imperial.ac.uk
Vietnam	98	Vietnam Academy of Science and Technology			

CubeSat Collaboration

Country		Group	Website	Contact Person	Email
Canada	99	Win-Cube: MSIG/MAHRCC/Mindset		Stefan Wagener	VE4NSA@amsat.org
Europe	100	European CubeSat Collaboration		Klaus Schilling	schi@informatik.uni-wuerzburg.de
US	101	FunSat - Florida University Collaboration		Kyle Schroedner	funsat@mail.ucf.edu
	102	Inland Northwest Space Alliance	http://www.inwspace.org/	Mike Miller	mmiller@inwspace.org
	103	StenSat	http://www.stensat.org/	Ivan Galysh	galysh@juno.nrl.navy.mil

High School

Country		School	Website	Contact Person	Email
US	104	Columbia High School (Georgia)			
	105	Leland High School (California)		Steve Schlink	steveschlink@aol.com
	106	Saratoga High School		Roxana Safipour	rsafipour@yahoo.com
	107	Wilcox High School		Lisa Kinneman	kinneman@pacbell.net

Commercial Participants

Country		Company/Coorperation	Website	Contact Person	Email
Czech Republic	108	EMP Centauri Ltd.		Marian Vana	info@emp-centauri.cz
Spain	109	GADESA, Galicia		Manuel Oreiro	manuel.oreiro@ingenierosvigo.com
US	110	Aerospace Corperation			
	111	Ecliptic Enterprises			
	112	The Boeing Company			
	113	Global Imaging			
	114	QuakeFinder		Tom Bleier	tbleier@stellersolutions.com
	115	Tethers Unlimited		Nestor Voronka	voronka@tethers.com
	116	Globaltec R & D Center		Judy Dragich Coenen	globaltec@dmv.com
	117	Global Imaging		Michael Guberek	mguberek@globalimaging.com
	118	Kentucky Science and Technology Corporation		Kris Kimel	kkimel@kstc.com

Government Organizations			
Country		Organization	Website, Contact Person and Email (if available)
Spain	119	Instituto Nacional de Técnica Aeroespacial	
US	120	NASA Ames Research Center	
	121	NASA Ames Marshall Space Flight Center	
	122	Kentucky Science and Technology Corporation	

APPENDIX B. CUBESAT T LAUNCHES

CubeSat Luanches from 2003 - August 2008

Launch Date	EELV Type	Launch Location	CubeSat Qty
June 30, 2003	Eurockot	Russia	6
	CubeSat Developer	**CubeSat Name**	**Country**
	Aalborg University	AAU CubeSat	Denmark
	Stanford Univerisity	QuakesSat	USA
	Technical Univ of Denmark	DTUSat	Denmark
	Tokyo Institute of Tech	CUTE-1	Japan
	University of Tokyo	XI-IV	Japan
	University of Toronto	CanX-1	Canada

Launch Date	EELV Type	Launch Location	CubeSat Qty
27 October, 2005	Cosmos-3M	Russia	3
	CubeSat Developer	**CubeSat Name**	**Country**
	Norwegian Univ of Sci & Tech	NCUBE2	Norway
	University of Tokyo	XI-V	Japan
	University of Wurzburg	UWE-1	Germany

Launch Date	EELV Type	Launch Location	CubeSat Qty
February 21, 2006	M-V	Japan	1
	CubeSat Developer	**CubeSat Name**	**Developer Country**
	Tokyo Institute of Technology	CUTE-1.7	Japan

*Launch Date	EELV Type	Launch Location	CubeSat Qty
26 July, 2006	Dnepr	Kazakstan	14
	CubeSat Developer	**CubeSat Name**	**Country**
	University of Illinois	ION	USA
	University of Kansas	KUTESAT-1	USA
	Norwegian University of Sci & Tech	NCUBE-1	Norway
	University of Arizona	RINCON 1	USA
	University of Arizona	SACRED	USA
	Montana State University	MEROPE	USA
	California Polytechnic State Univ	CP-1	USA
	California Polytechnic State Univ	CP-2	USA
	Cornell University	ICECUBE 1	USA
	Cornell University	ICECUBE 2	USA
	Hankuk Aviation University	HAUSAT-1	Korea
	Nihon University	SEEDS	Japan
	University of Hawaii	Voyager	USA
	Aerospace Corperation	AeroCube 1	USA
*Note:	This launch failed to make orbit		

Launch Date	EELV Type	Launch Location	CubeSat Qty
December 16, 2008	Minotaur	USA	1
	CubeSat Developer	**CubeSat Name**	**Developer Country**
	NASA Ames	GeneSat-1	USA

Launch Date	EELV Type	Launch Location	CubeSat Qty
April 17, 2007	Dnepr	Kasakstan	7
	CubeSat Developer	**CubeSat Name**	**Country**
	Boeing	CSTB1	USA
	University of Sergio Arboleda	Libertad 1	Columbia
	University of Louisiana at Lafayette	CAPE1	USA
	California Polytechnic State Univ	CP-3	USA
	California Polytechnic State Univ	CP-4	USA
	Aerospace Corperation	AeroCube 2	USA
	Tethers Unlimited, Inc.	MAST	USA

Launch Date	EELV Type	Launch Location	CubeSat Qty
April 28, 2008	PSLV	India	6
	CubeSat Developer	**CubeSat Name**	**Country**
	Aalborg University	AAUSAT-II	Denmark
	University of Toronto	CanX-2	Canada
	University of Applied Sciences	Compass-1	Germany
	Tokyo Institute of Technology	CUTE-1.7+APD II	Japan
	Delft University of Technology	Delfi C3	Netherlands
	Nihon University	SEEDS-II	Japan

*Launch Date	EELV Type	Launch Location	CubeSat Qty
August 2, 2008	Falcon 1	USA	2
	CubeSat Developer	**CubeSat Name**	**Developer Country**
	NASA Marshall	PRESat	USA
	NASA Marshall	NanoSail-D	USA
*Note:	This launched failed to make orbit		

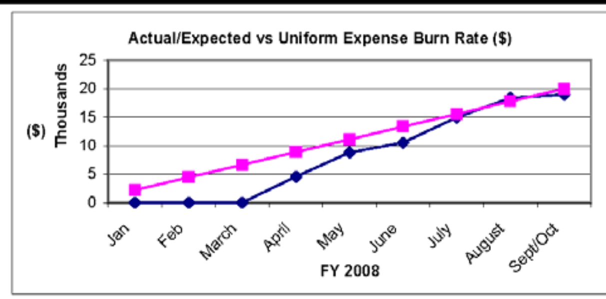
APPENDIX C. NPSCUL BUDGET

Appendix C - NPS Cube Sat Launcher Budget FY2008

	Jan	Feb	March	April	May	June	July	August	Sept/Oct	Yearly Total	Target (Set at beginning of year)
Travel	**0.00**	**0.00**	**0.00**	**1,183.51**	**1,227.51**	**0.00**	**3,081.34**	**2,291.57**	**402.00**	**8,185.93**	**4,000.00**
Students	0.00	0.00	0.00	1,183.51	1,227.51	0.00	3,081.34	2,291.57	402.00	8,185.93	2,400.00
Equipment & Supplies	**0.00**	**0.00**	**0.00**	**2,285.00**	**1,996.93**	**1,315.00**	**281.59**	**300.00**	**75.96**	**6,254.48**	**11,198.00**
a) E&S less than $15k	0.00	0.00	0.00	2,285.00	1,996.93	1,315.00	281.59	0.00	75.96	5,954.48	10,598.00
Structure (Aluminum)								0.00		0.00	
P-Pod										0.00	
3D Printer Rental				1,500.00	1,000.00					2,500.00	
3D Printer Material				785.00		1,315.00				2,100.00	
Miscellaneous										0.00	
Rhino Software					205.00					205.00	
Springs					142.92		56.05			198.97	
Servo Equipment					649.01					649.01	
Stamp Controller							225.54			225.54	
Pelican Foam									75.96	75.96	
										0.00	
b) E&S greater than $15k										0.00	0.00
c) Software and support										0.00	0.00
d) Miscellaneous								300.00		300.00	600.00
Indirect Cost	**0.00**	**0.00**	**0.00**	**1,095.70**	**1,018.60**	**415.41**	**1,062.35**	**818.68**	**150.99**	**4,561.73**	**4,801.05**
Total Expenses	**0.00**	**0.00**	**0.00**	**4,564.21**	**4,243.04**	**1,730.41**	**4,425.28**	**3,410.25**	**628.95**	**19,002.14**	**19,999.05**
Actual Cumulative Expenses	0.00	0.00	0.00	4,564.21	8,807.25	10,537.66	14,962.94	18,373.19	19,002.14		
Uniform Burn rate	*2,222.22*	*4,444.44*	*6,666.67*	*8,888.89*	*11,111.11*	*13,333.33*	*15,555.56*	*17,777.78*	*20,000.00*		

Travel Cost Break-down

Travel Notes:	Per person	# people	Total	Actual
April 2008 CubeSat Dev Workshop	450	2	900	$764.71
April 29th CSEWI	450	1	450	$418.80
May 2008 Rideshare Wallups, VA	1200	1	1500	$1,227.51
July 2008 Navy SERB	1500	2	3000	$3,081.34
Aug 2008 Small Sat	1500	2	3000	$2,291.57
Oct 2008 DoD SERB				$402.00
Total			**8850**	$8,185.93



Purchase Orders	Date	Price	Shipping	Total
3D Printer Material	4/1/08	$750.00	$35.00	$785.00
Rhino CAD Program + Shipping	5/1/08	$195.00	$10.00	$205.00
McMaster Carr - Springs	5/12/08	$67.56	$4.50	$72.06
Servo City - Servos	5/13/08	$341.94	$49.69	$391.63
Servo City - Servos	5/29/08	$245.38	$12.00	$257.38
McMaster Carr - Springs	5/29/08	$66.36	$4.50	$70.86
3D Printer Material	6/3/08	$750.00	$40.00	$790.00
3D Printer Material	6/9/08	$500.00	$25.00	$525.00
Stamp Controller	7/21/08	$194.85	$30.69	$225.54
McMaster Carr - Springs	7/29/08	$51.30	$4.75	$56.05
Pelican Foam	10/9/08	$63.81	$12.15	$75.96
			Total	**$3,454.48**

Services	Date	Price	Shipping	Total
Lease for Dimension Printer (5 April - 4 May)	4/1/08	$1,000.00	$500.00	$1,500.00
Lease for Dimension Printer (5 May - 4 June)	5/1/08	$1,000.00	$0.00	$1,000.00
Small Sat Conference Fee's	Crook	Matt	$0.00	$150.00
Small Sat Conference Fee's	Hicks	Christina	$0.00	$150.00
			Total	**$2,800.00**

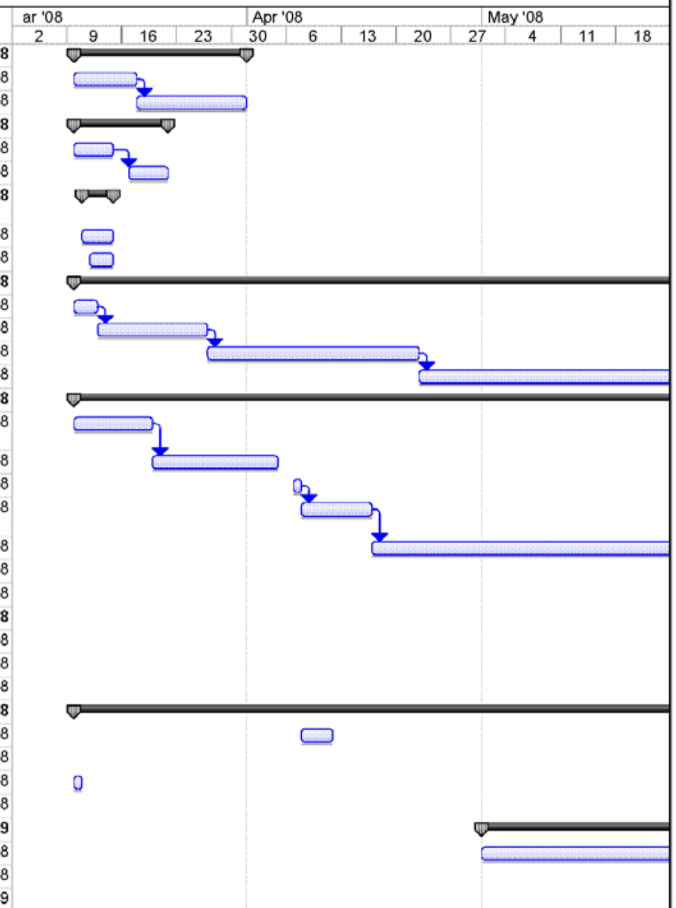
Travel

Destination and Purpose	Last Name	First Name		Total
Cal Poly - CubeSat Workshop	McKoy	AJ		$421.34
Cal Poly - CubeSat Workshop	Crook	Matt		$343.37
Wallups, VA - Rideshare Conference	Crook	Matt		$1,227.51
Los Angeles - CSEWI Partners Meeting	Crook	Matt		$418.80
Washington DC - NRL - DoN SERB	Crook	Matt		$1,588.32
Washington DC - NRL - DoN SERB	Hicks	Christina		$1,493.02
Logan Utah - Small Sat Conf	Crook	Matt		$1,216.54
Logan Utah - Small Sat Conf	Hicks	Christina		$1,075.03
DoD SERB	Hicks	Christina		$402.00
			Total	**$8,185.93**

APPENDIX D. SCHEDULE

Appendix D - NPSCuL Schedule FY08

ID	Task Name	Duration	Start	Finish
1	**Budget**	**16 days**	**Mon 3/10/08**	**Mon 3/31/08**
2	Complete Initial Budget	6 days	Mon 3/10/08	Mon 3/17/08
3	Revised Budget	10 days	Tue 3/18/08	Mon 3/31/08
4	**Schedule**	**10 days**	**Mon 3/10/08**	**Fri 3/21/08**
5	Complete Initial Schedule	5 days	Mon 3/10/08	Fri 3/14/08
6	Revised Schedule	5 days	Mon 3/17/08	Fri 3/21/08
7	**Cal-Poly CubeSat Conf**	**4 days**	**Tue 3/11/08**	**Fri 3/14/08**
8	Complete Abstract	4 days	Tue 3/11/08	Fri 3/14/08
9	Complete Poster	3 days	Wed 3/12/08	Fri 3/14/08
10	**NPSCul Structure**	**62 days**	**Mon 3/10/08**	**Tue 6/3/08**
11	Complete NPSCul Drawings & Details	3 days	Mon 3/10/08	Wed 3/12/08
12	Glenn on Vacation	10 days	Thu 3/13/08	Wed 3/26/08
13	Build NPSCul Poly Carbonate Structure	19 days	Thu 3/27/08	Tue 4/22/08
14	Build NPSCuL Aluminum Structure	30 days	Wed 4/23/08	Tue 6/3/08
15	**P-Pod Models**	**103 days**	**Mon 3/10/08**	**Wed 7/30/08**
16	Investigate Options for 3D Printer	8 days	Mon 3/10/08	Wed 3/19/08
17	Arrainge for use of a 3D Pritner (Lease)	12 days	Thu 3/20/08	Fri 4/4/08
18	Aquire 3D Printer and Material	1 day	Mon 4/7/08	Mon 4/7/08
19	Aquire Materials for 3D Printer	7 days	Tue 4/8/08	Wed 4/16/08
20	Build P-POD Models	75 days	Thu 4/17/08	Wed 7/30/08
21	Build Servo Controller	21 days	Mon 6/30/08	Mon 7/28/08
22	Build Sequencer Box	14 days	Tue 7/8/08	Fri 7/25/08
23	**Process & Requirements Document**	**109 days**	**Tue 7/1/08**	**Fri 11/28/08**
24	First Cut	24 days	Tue 7/1/08	Fri 8/1/08
25	Second Cut	51 days	Mon 8/4/08	Mon 10/13/08
26	Final, Version 1.0	34 days	Tue 10/14/08	Fri 11/28/08
27	**Travel**	**114 days**	**Mon 3/10/08**	**Thu 8/14/08**
28	Conference	4 days	Tue 4/8/08	Fri 4/11/08
29	Rideshare Conference in Wallups, VA	3 days	Mon 7/7/08	Wed 7/9/08
30	Navy Space Experiments Review Board	1 day	Mon 3/10/08	Mon 3/10/08
31	Small Satellite Conference in Logan, UT	4 days	Mon 8/11/08	Thu 8/14/08
32	**Thesis**	**181 days**	**Thu 5/1/08**	**Thu 1/8/09**
33	Thesis Rough Draft	88 days	Thu 5/1/08	Mon 9/1/08
34	Thesis Second Cut	79 days	Tue 9/2/08	Fri 12/19/08
35	Final Cut	14 days	Mon 12/22/08	Thu 1/8/09



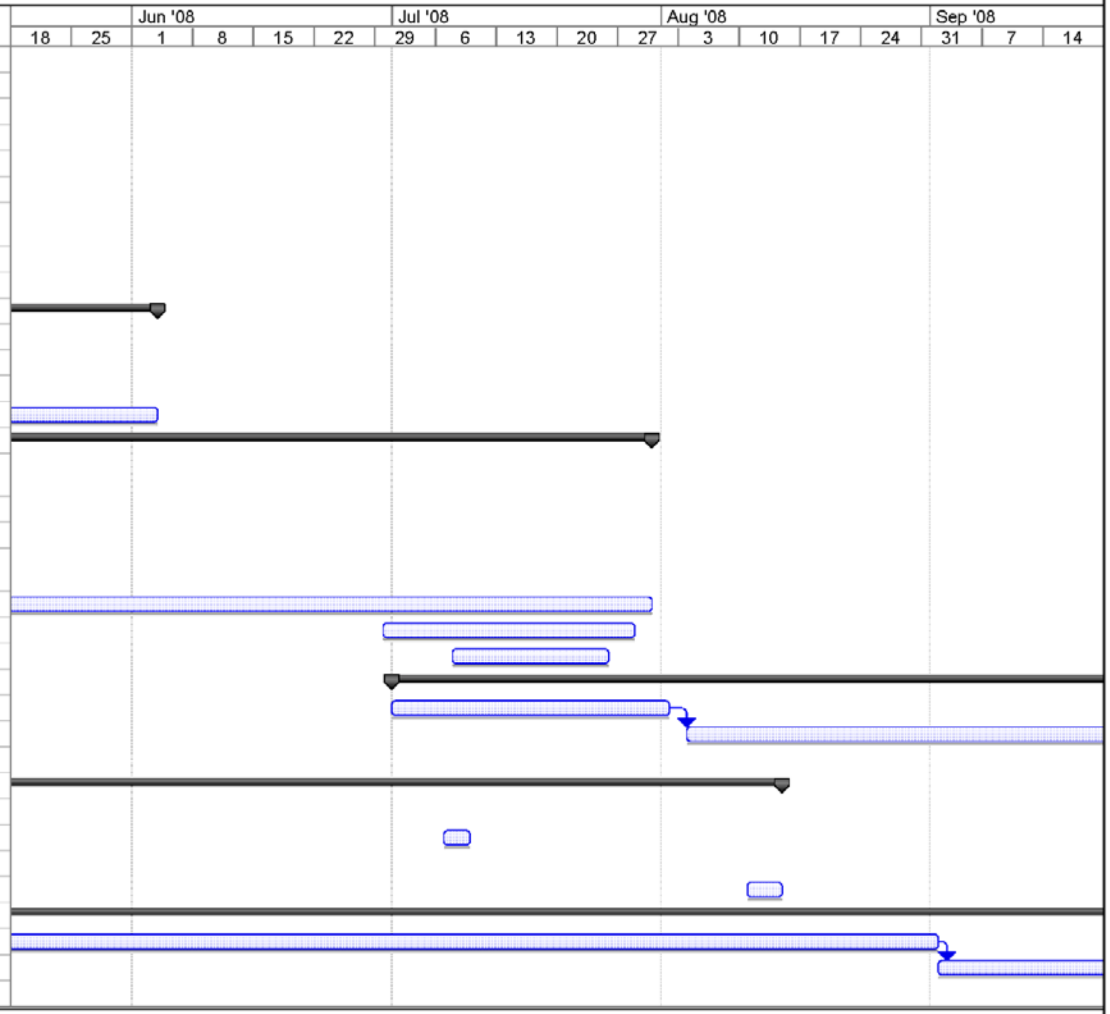
Project: Schedule
Date: Fri 12/12/08

Task | Split | Progress | Milestone | Summary | Project Summary | External Tasks | External MileTask | Split

Page 1

Appendix D - NPSCuL Schedule FY08

ID	Task Name
1	**Budget**
2	Complete Initial Budget
3	Revised Budget
4	**Schedule**
5	Complete Initial Schedule
6	Revised Schedule
7	**Cal-Poly CubeSat Conf**
8	Complete Abstract
9	Complete Poster
10	**NPSCul Structure**
11	Complete NPSCul Drawings & Details
12	Glenn on Vacation
13	Build NPSCul Poly Carbonate Structure
14	Build NPSCuL Aluminum Structure
15	**P-Pod Models**
16	Investigate Options for 3D Printer
17	Arrainge for use of a 3D Pritner (Lease)
18	Aquire 3D Printer and Material
19	Aquire Materials for 3D Printer
20	Build P-POD Models
21	Build Servo Controller
22	Build Sequencer Box
23	**Process & Requirements Document**
24	First Cut
25	Second Cut
26	Final, Version 1.0
27	**Travel**
28	Conference
29	Rideshare Conference in Wallups, VA
30	Navy Space Experiments Review Board
31	Small Satellite Conference in Logan, UT
32	**Thesis**
33	Thesis Rough Draft
34	Thesis Second Cut
35	Final Cut



Project: Schedule
Date: Fri 12/12/08

Task		Milestone		External Tasks	
Split		Summary		External MileTask	
Progress		Project Summary		Split	

Appendix D - NPSCuL Schedule FY08

ID	Task Name
1	**Budget**
2	Complete Initial Budget
3	Revised Budget
4	**Schedule**
5	Complete Initial Schedule
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7	**Cal-Poly CubeSat Conf**
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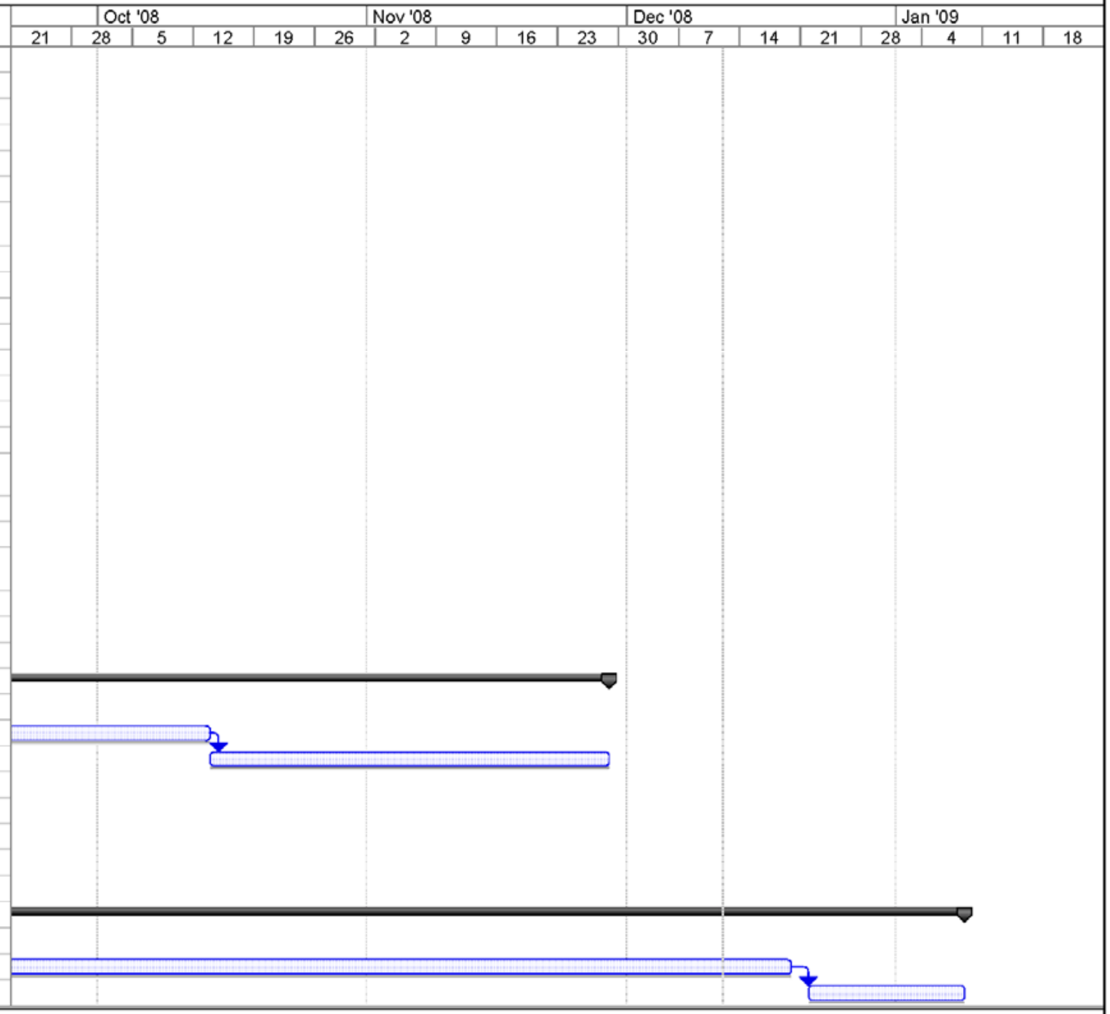
34	Thesis Second Cut
35	Final Cut



Project: Schedule
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APPENDIX E. NPSCUL PROCESS AND REQUIREMENTS DOCUMENT

Naval Postgraduate School CubeSat Launcher (NPSCuL)

Space-Available Manifesting Process and Requirements

Version 1

November 30, 2008

Naval Postgraduate School

Space Systems Academic Group

Approved for public release; distribution is unlimited

UNCLASSIFIED

THE PRE-LAUNCH AND LAUNCH ENVIRONMENT:

The Launch environment varies for each secondary payload adapter. For complete details please see the appropriate secondary payload planner's guide.

In the spirit of not impacting the primary payload, expect requirements to be imposed that support this objective. For example, it is possible that a CubeSat developer may not have access to their CubeSat once delivered to Cal Poly, and it could be up to six months from time of delivery to launch. Therefore CubeSat developers should not expect to be recharge or access their CubeSats during this time.

The specific environmental testing requirements for each launch will be a combination of the requirements found in the applicable secondary payload planners guide, the CDS, and any additional requirements on a mission unique basis. Specifics requirements for each launch, including mission unique requirements will be released shortly after the NPSCuL manifesting process begins. In general requirements should be consistent with the pre-launch and launch environments found in the applicable secondary payload planner's guide and the CDS.

ACKNOWLEDGEMENTS

The Department of Labor's WIRED initiative through the CSEWI made the research and development of NPSCuL possible during the 2008 fiscal year. The partnership with CSEWI and funding provided were invaluable to the project.

ACRONYMS

ABC	-	Aft Bulkhead Carrier
Cal Poly	-	The California Polytechnic State University (San Luis Obispo)
CDS	-	CubeSat Design Specification - maintained and released by Cal Poly
CSEWI	-	California Space Education & Workforce Institute
DoD	-	Department of Defense
EELV	-	Evolved Expendable Launch Vehicle
ESPA	-	EELV Secondary Payload Adapter
NCQ	-	NPSCuL CubeSat Queue
NPS	-	Naval Postgraduate School
NPSCuL	-	NPS CubeSat Launcher
NPC	-	NPSCuL Payload Coordinator
P-POD	-	Poly Picosatellite Orbital Deplorer
SERB	-	(STP) Space Experiments Review Board
STP	-	Space Test Program
WIRED	-	Workforce Innovation in Regional Economic Development

INTRODUCTION

The Naval Postgraduate School (NPS) CubeSat Launcher (NPSCuL, pronounced "NPS cool") is a high-capacity CubeSat launcher designed to work with US evolved expendable launch vehicles (EELV). NPSCuL is an adapter that can attach multiple California Polytechnic State University (Cal Poly) Pico-satellite Orbital Deployers (P-POD) to a single EELV Secondary Payload Adapter (ESPA) slot. NPSCuL is a simple and inexpensive adapter that should allow these proven technologies to be used jointly, thereby facilitating high-capacity US based CubeSat launches on US Government, Department of Defense (DoD), and Commercial ESPA compatible launch vehicles.

There are two varieties of NPSCuL, "Standard" and "Lite". NPSCuL-Standard has 10 slots for 3U or 5U P-PODs. Additionally 6U (also known as the NASA Ames "six pack") P-POD can be accommodated by using two slots each. NPSCuL-Lite has 8 slots which can accommodate 3U P-PODs or 6U P-PODs. NPSCuL-Standard has been developed to maximize capacity for use on the EELV ESPA adapters. NPSCuL-Lite, while still ESPA compatible is designed for use on smaller secondary payload adapters, such as the Atlas V Aft Bulkhead Carrier (ABC), having less volume and mass .

The purpose of this document is to describe the current method to manifest non-US Government DoD-relevant payloads on US government sponsored space launches, and to introduce a new process to manifest non-Government CubeSat payloads on a space-available basis on US Government space launches through NPSCuL. Government payloads and CubeSats may be manifested through processes already in place such as the US Air Force (USAF) Space Test Program (STP).

THE DOD SERB PROCESS OVERVIEW:

The STP is part of the Air Force Space Development and Test Wing at Kirkland AFB in Albuquerque, New Mexico, and was created in 1965 with the purpose of providing spaceflight for the DoD research community. From creation until present, STP has facilitated launch for over 120 missions using dedicated free-flyers, the space shuttle, and other piggyback payload opportunities.

Since there are more experiments requesting space launch opportunities than are possible to launch, the STP reviews and ranks experiments through the DoD Space Experiments Review Board (SERB) process. Experiments which compete for launch through the DoD SERB must be sponsored by a DoD agency. Although typically originating from one of the DoD services, laboratories, or research institutions, experiments can also come from other federal agencies or U.S. universities. Partnerships between non-DoD and DoD experimenters qualify for consideration in the SERB process.

The DoD SERB meets in October or November of each year and the panel consists of representatives of the various services and other DoD agencies and partners, such as NASA. Each experiment will be presented to the panel by the DoD sponsoring agency, after which each experiment is ranked according to DoD relevance, experiment quality, and service priorities. The SERB produces a prioritized list of space experiments.

Each rideshare opportunity for launching a SERB payload is analyzed, including launch mass margin, mission sensitivity, orbital parameters, and other constraints for compatibility with STP secondary payload experiments. The DoD SERB list is used to identify experiments which may be best suited for the rideshare mission. The STP will requires comprehensive technical information on each experiment identified for possible manifestation onboard the launch. The remaining process varies and depends on the complexity and unique requirements of the mission.

There is no standard process to gain sponsorship from a DoD agency by a non-DoD experiment provider. If a non-DoD space experiment developer felt their experiment was of some DoD relevance, and wanted to find a launch opportunity through

the SERB process, they should contact individual DoD agencies and request an opportunity to present their experiment to that agency. If an agency found an experiment to be of particular interest and wanted to become a partner in the experiment, it may choose to sponsor and present the experiment to the DoD SERB. Experiments not of interest to the DoD would probably find it difficult to find a DoD sponsor. Nano-satellites and CubeSat developers, even if they have a satellite of DoD relevance, may find the STP rideshare process arduous since it typically serves larger (400 lb – 6000 lb) secondary payloads, by their nature, more complex, with higher budgets and more team members than usually found with nano-satellite and CubeSat developers. While NPSCuL fills the needs of the DoD and SERB process, it should also enable non-DoD CubeSat developers to fly on a space-available basis. The next section of this document describes that process.

THE NPSCUL MANIFESTING PROCESS OVERVIEW:

NPSCuL is a means to provide CubeSat launch on US EELV compatible launch vehicles. NPSCuL-Standard and NPSCuL-Lite are both compatible with the ESPA. In addition to the ESPA, NPSCuL-Lite is compatible with other secondary payload adapters such as the new ABC adapter being developed for Atlas V launch vehicles, and may be compatible with an adapter for NASA's Minotaur rocket.

NPSCuL has been presented to the STP SERB and has received a favorable ranking on the SERB list. NPSCuL was presented as an experiment, but also it is an enabling technology for deploying a large volume of CubeSats. While it is expected that the NPSCuL will be manifested by the STP to enable launch for DoD CubeSat payloads on the SERB list, it is possible that NPSCuL could be manifested by other government flight providers when necessary to launch specific government CubeSat payloads.

Although the primary motivation for STP, or any other government launch provider, to launch an NPSCuL may be to provide a launch opportunity for DoD CubeSat payloads, DoD experiments may not necessarily use the entire NPSCuL CubeSat payload capacity. When excess CubeSat launch capacity is available, rather than waste the remaining CubeSat payload capacity NPS has developed a process to provide launch opportunities for non-DoD educational and commercial CubeSat developers not traditionally served by the SERB process.

NPS expects certification requirements to launch on NPSCuL to be consistent with those already required for launch by most CubeSat launch providers. CubeSats interested in being manifested on NPSCuL must, at a minimum, have the ability to communicate with a ground station and serve some useful national, scientific, or educational purpose. US developers launching on NPSCuL will have the added benefit of avoiding many, if not all, ITAR related complications often encountered on foreign launches. While launch onboard NPSCuL is expected to be free, the cost of integrating a developer's CubeSat into a P-POD are expected to be similar to current Cal Poly integration costs.

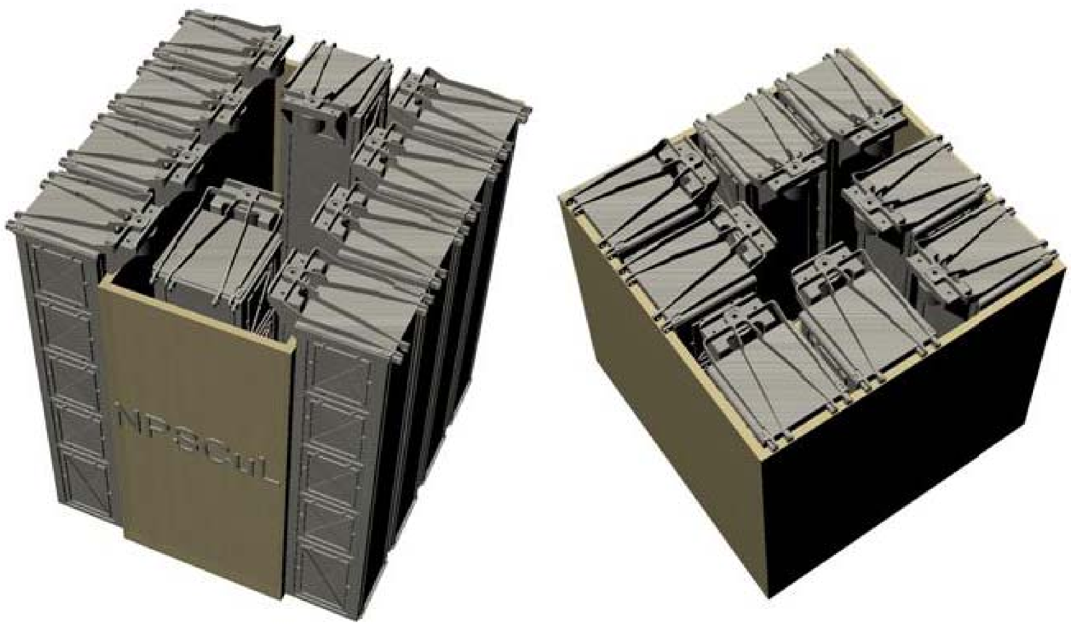

Figure 1 – NPSCuL-Standard (Left) and NPSCuL-Lite (Right)

The NPS Space Systems Academic Group will be responsible for all aspects of the NPSCuL launcher, including construction, testing, and integration of loaded P-PODs with NPSCuL. NPS will make all necessary arrangements with the appropriate US Government flight provider, typically the STP, and will work with Cal Poly regarding P-POD acquisition and CubeSat to P-POD integration.

Domestic CubeSat developers will be listed on the NPSCuL CubeSat Queue (NCQ) on a first-come, first-serve basis. CubeSat developers seeking space-available deployment by NPSCuL will be offered opportunities in the order they fall on the NCQ. Developers requesting launch for multiple CubeSat experiments will be permitted one CubeSat experiment per launch, with their other CubeSat experiments then in line for the next launch or potentially as current backups. To be included on the NCQ a developer needs to complete the form included at the end of this document and mail or email a copy to NPS. Details for mail and email are found on the questionnaire. Once received, NPS will notify the sender of receipt and confirm their CubeSat payload has been placed on the NCQ, including the date and time their completed questionnaire was received for purposes of NCQ listing order. After all available domestic CubeSats have been

manifested on NPSCuL, any remaining space-available capacity may be allocated for CubeSat launch for our international CubeSat partners. While the intent is to launch on a first-come, first-serve basis, the US Government reserves the right to launch any CubeSat in whatever order deemed to be in the national interest.

CubeSat developers should contact Cal Poly as early as possible to verify proper testing requirements for their CubeSat payloads. Some typical testing and documentation that should be expected for all CubeSat includes random vibration testing, multiple bake-out cycles and associated documentation, and a materials list for all materials in their CubeSat. The testing required by Cal Poly is to guarantee that each CubeSat payload will not present a hazard to the primary payload or other secondary payloads including other CubeSats in the same P-POD. Testing required by Cal Poly is not designed to guarantee CubeSat functionality after deployment – each CubeSat developer is individually responsible to conduct whatever testing and analysis is necessary to guarantee functionality of their CubeSat payloads after launch and deployment.

When a flight opportunity is announced and the launch date and orbital parameters are known, CubeSat developers will be asked to state whether they are interested in that opportunity or whether they want to pass until the next opportunity. Once NPS knows the expected number of space-available slots on NPSCuL, CubeSats on the NCQ will be assigned a status of "tentatively manifested" or "tentative alternate". The "tentative" before each label meaning that this is their intended status but can not yet be confirmed until STP provides the final number of space-available slots to NPS. The purpose of assigning tentative status categories is to allow CubeSat developers as much notice as possible of possible flight opportunities. NPS will assign CubeSats on the NCQ the status of "manifested" and "alternate" after the final number of space-available slots is confirmed by STP and after STP approves the proposed manifest and alternate lists. Manifested status indicates the CubeSat is manifested to use one of the space-available slots. Alternate status indicates a CubeSat part of the group who are in line for launch if any of the manifested CubeSats (both space-available manifested and DoD manifested) fail to make launch. There may be multiple CubeSats in any status category. Once begun, the NCQ will remain a single continuous list, or queue across multiple launches. This avoids tying specific CubeSats only to specific flights, but allows more flexibility in

scheduling. If CubeSats on the NCQ are not able to make a launch, they will keep their position in line for the next available launch.

Developers with CubeSats on the NCQ will be informed of their status as soon as possible so they can commence preparations and begin coordinating efforts between themselves and Cal Poly. To prevent launching NPSCuL with empty slots that could have been used by other CubeSat developers it is imperative that CubeSat developers meet certain milestones once manifested for flight on NPSCuL. The specific milestone schedule will be released at the same time or shortly after the announcement to solicit CubeSats for launch. A milestone review will take place ten months before launch. Any CubeSats which have not met the necessary milestones may be required to undergo a second review two months later and possibly be de-manifested. If the necessary milestones are still incomplete at the second review, to ensure NPSCuL is fully loaded for launch, CubeSats on the alternate list which have met their milestones may be manifested. Informal status and coordination between formal reviews will take place as needed.

TYPICAL TIMELINE FOR NPSCUL LAUNCH

L – 24 months:	NPSCuL chosen for flight by STP
L – 24 months:	NPS releases announcement for CubeSat launch.
L – 20 months:	NPS notified by STP of the tentative number of space-available CubeSat payload slots. Tentative space-available manifest list distributed by NPS including back-up list as soon as possible thereafter.
L – 15 months:	STP notifies NPS of the number of space-available CubeSat payload slots. NPS distributes the manifest and alternate lists for the launch.
L – 10 months:	Formal milestone review of manifested and back-up CubeSats. Manifested CubeSats that have not met the necessary milestones may be required to undergo a second milestone review in two months.
L – 9 months:	CubeSat to P-POD fit check at Cal Poly.
L – 8 months:	Second milestone review for any manifested CubeSats which failed to complete necessary milestones at the L-10 month review. Manifested CubeSats may be replaced with back-up CubeSats at this time if necessary milestones remain incomplete.
L – 5 months:	CubeSats delivered to Cal Poly for integration and testing.
L – 4 months:	P-PODs delivered to NPS for integration onto NPSCuL
L – 3 months:	NPSCuL delivered to STP for integration onto launch vehicle.
L – 0 months:	Launch

GENERAL GUIDELINES FOR ALL CUBESAT PAYLOADS.

All CubeSat payloads should adhere to the following guidelines; exceptions are highly discouraged and may disqualify a CubeSat for flight. Any exceptions should be discussed with the NPS as early as possible.

1) CubeSats developers must fill out the attached questionnaire describing their CubeSat and its required orbital parameters.

2) CubeSats must serve some useful national, scientific or educational purpose.

3) CubeSats must have the ability to communicate with a ground station.

4) CubeSats may not request an orbit that would cause their CubeSat to remain in orbit longer than 25 years after the end of their mission, unless they have received a waver from the FCC. CubeSat developers are solely responsible for requesting and acquiring any wavers if necessary. Unless a waver is obtained, CubeSat developers are required to calculated the orbital lifetime after mission end and provide this calculation to NPS.

5) CubeSats should meet all requirements outlined in the most current revision of the CubeSat Design Specification (CDS) published by the California Polytechnic State University (Cal Poly).

6) The most current version can be found at the following website: http://cubesat.atl.calpoly.edu/media/Documents/Developers/CDS%20R9.pdf

7) CubeSats must pass qualification and acceptance testing for the Pre-launch and Launch environment outlined in the most current revision of the appropriate Secondary Payload Planners Guide and provide appropriate documentation to Cal Poly.

   The most current version of the ESPA Payload Planners Guide can be found at the following website:

http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA435515&Location=U2&doc=GetTRDoc.pdf

8) It is recommended that CubeSats meet minimum cleanliness requirements of class 100,000 cleanroom.

9) CubeSats may not impose requirements on the launch provider or program office.

10) In general, due to the large number of potential CubeSat developers, space-available CubeSat developers chosen for launch should direct any communication with the launch provider through the Cal Poly and NPSCuL Payload Coordinators.

11) Additional testing and requirements could possibly be required by the Primary Payload. If so, this will be provided as soon as it is known.

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APPENDIX F. NPSCUL CUBESAT QUEUE QUESTIONNAIRE

NPSCuL CubeSat Queue (NCQ) Questionnaire

Once Complete Email or Mail this Application to one of the following:	Email: NPSCuL@nps.edu Mail: Naval Postgraduate School NPSCuL Team 215 Bullard Hall Monterey, CA 93943

CubeSat Name:		
Short Description:		
Administrative Contact:		Title:
Organization:		
Street:		
Street:		
City:		
Postal Code:		Country:
Phone Number:		
Email:		
Website:		

Initial Launch Capability (Date):	
Mission Duration:	

Desired Orbital Parameters			
Apogee (km):	+/- (km)	Perigee (km):	+/- (km)
Inclination:	+/- (deg)		
Estimated orbital Lifetime after mission completion:	Shortest (months)(largest apogee/perigee):		
	Longest (months)(smallest apogee/perigee):		
Describe basis for shortest/longest orbital lifetime calculation after mission completion (included atmospheric model, reasoning, etc):			

(Page 1 of 3)

Other orbital parameters / notes:
Should NPS contact you about potential launch opportunities even if the orbital parameters do not meet your desired orbital parameters? YES / NO (Circle one)

Are there any pressure vessels on the CubeSat? (If so list pressure vessel type, contents and pressure)
Does the CubeSat contain hazardous materials? (If so list type and quantity)
Is there any onboard Propulsion? (If so please describe including propellant type, etc)
Are there any deployable structures? (If so please describe)
Are there any special considerations? (Safety, ITAR, classification level, proprietary, etc.):

(Page 2 of 3)

NCQ Questionnaire (Continued)

Abstract: In 500 words or less describe the mission of the CubeSat.

Note: If desired, attach a more comprehensive description of your CubeSat (no more than 8 pages) as necessary.
(Page 3 of 3)

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